The DarkSide Direct Dark Matter Search with Liquid Argon

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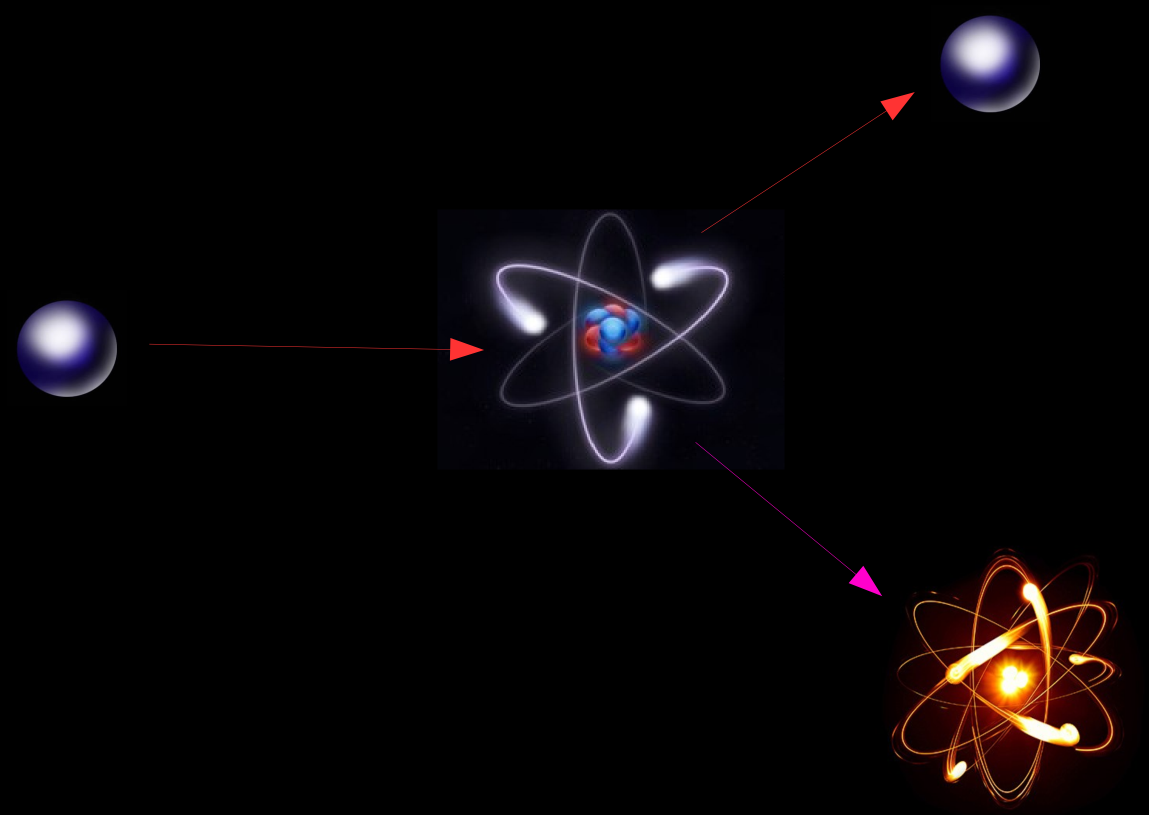
CETUP 2016 – Lead, South Dakota

Direct Detection

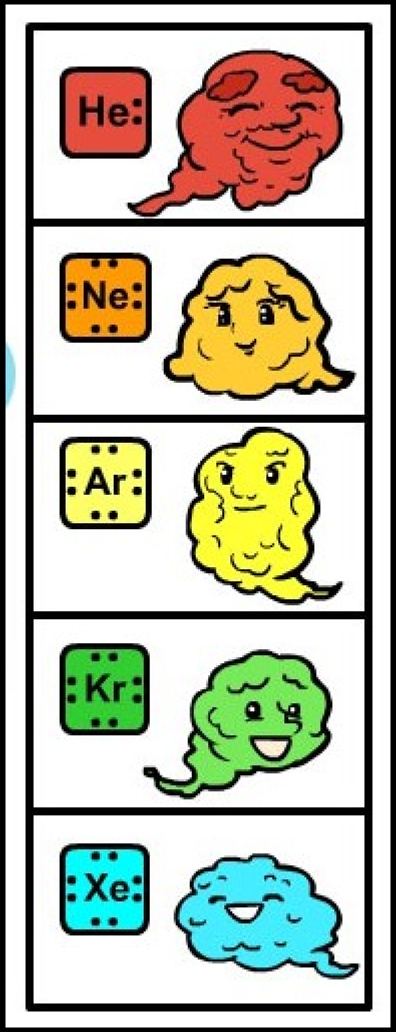
In *principle*, direct detection of dark matter is very simple:



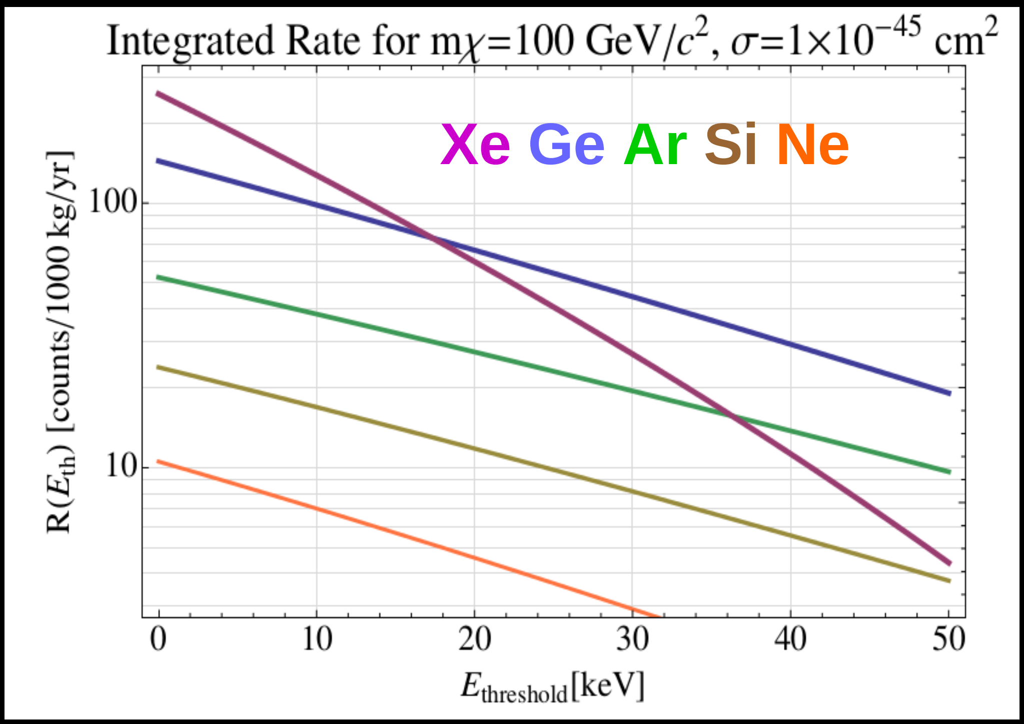
Liquid Noble Targets

Liquid noble elements are excellent for WIMP dark matter detection:

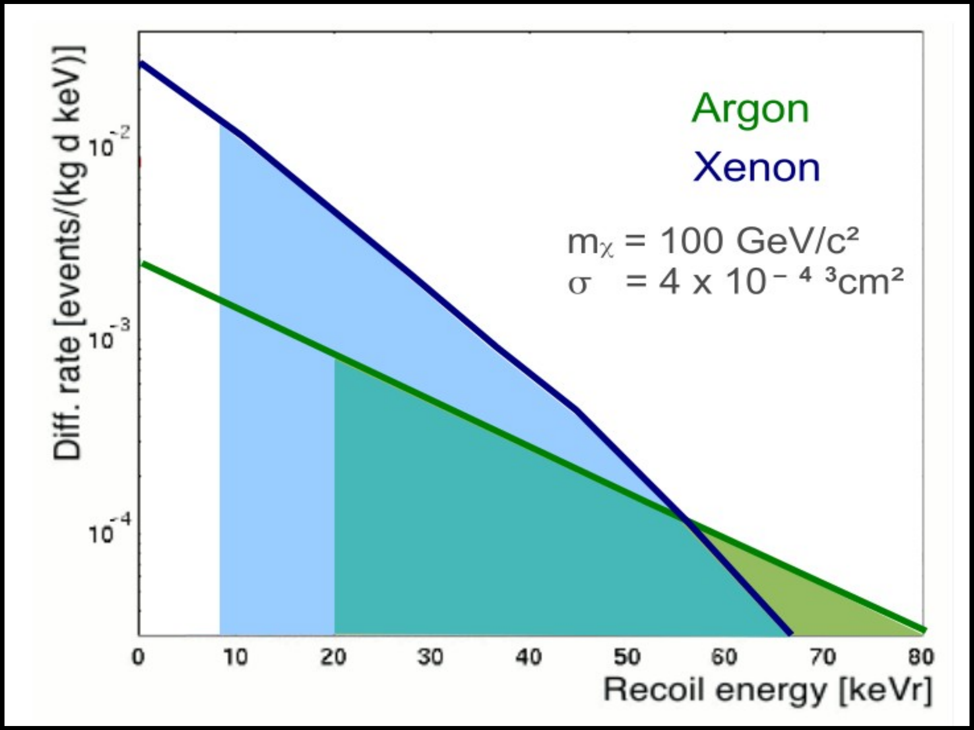
- Good scintillators (and ionizers)
  → 40 photons/keV in argon
  → nuclear / electron recoil discrimination
- Transparent to their own scintillation light
- Can be purified
- Self shielding
  → short interaction length for gammas gives inner fiducial region with low background rate
- Scalable to larger detector sizes



Liquid Noble Targets



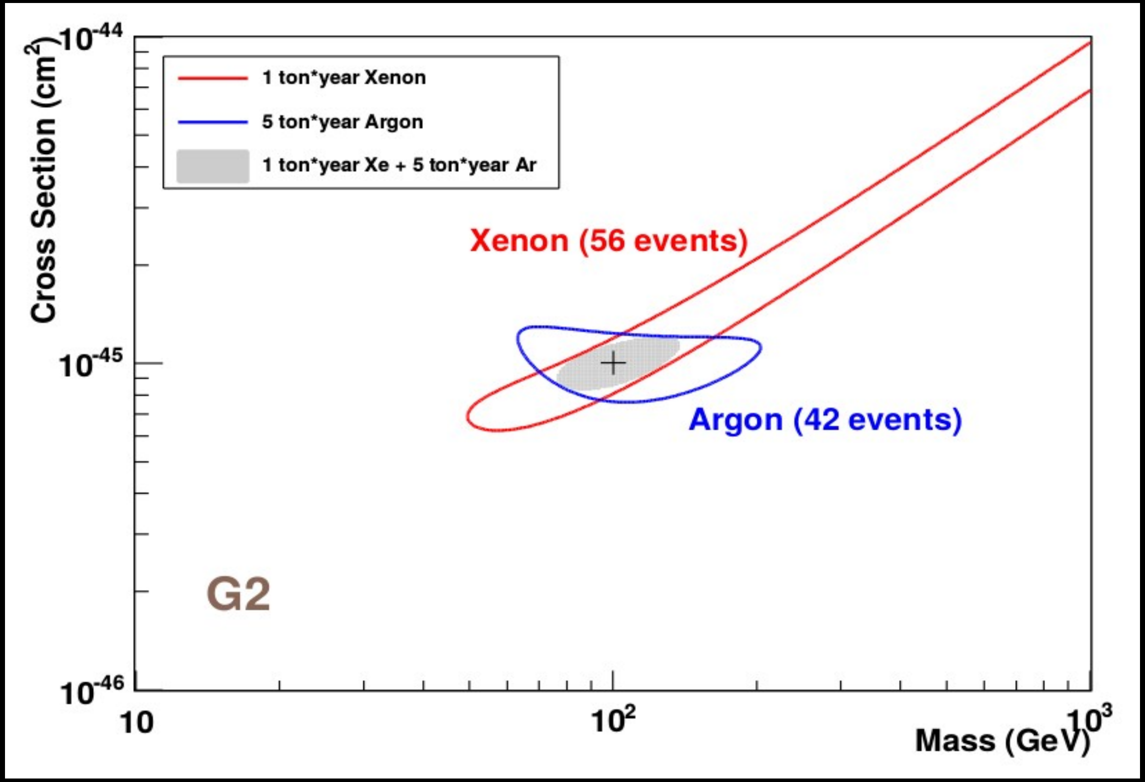
arXiv.1310.8327v2



arXiv:1206.2169

The interaction rate is higher in xenon than in argon for low recoil energies, but is form factor suppressed at higher energies

Liquid Noble Targets



arXiv.1310.8327v2

In the event of discovery, multiple detector targets are necessary to break the mass / cross section degeneracy

A Tiny Signal in a Crowd of Backgrounds

- Expected rate for 100 GeV WIMP with 10^{-45} cm^2: ~10^{-4} events/kg/day
  → Tiny rate!

- Many sources of background can create a signal in the detector:
  - Cosmogenic backgrounds:
    → Muons, neutrons
  - Radiogenic backgrounds:
    → Neutrons (from (α,n) + fission)
    → β, γ (from detector materials)

Neutrons produce an especially dangerous class of background, as they imitate the expected WIMP signal

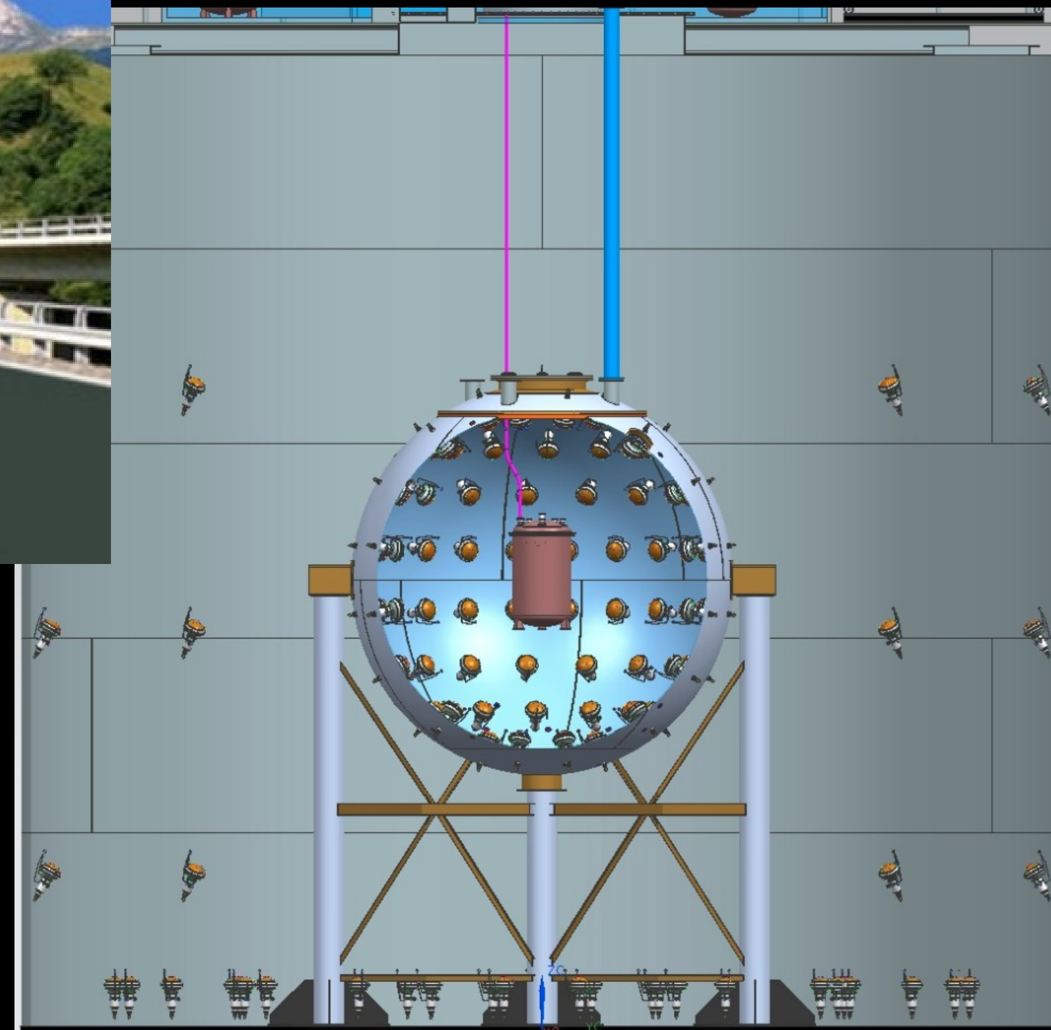
Background Mediation

Need multiple strategies for background mediation!

- Cosmogenic backgrounds:
  → Passive shielding
  → Active veto

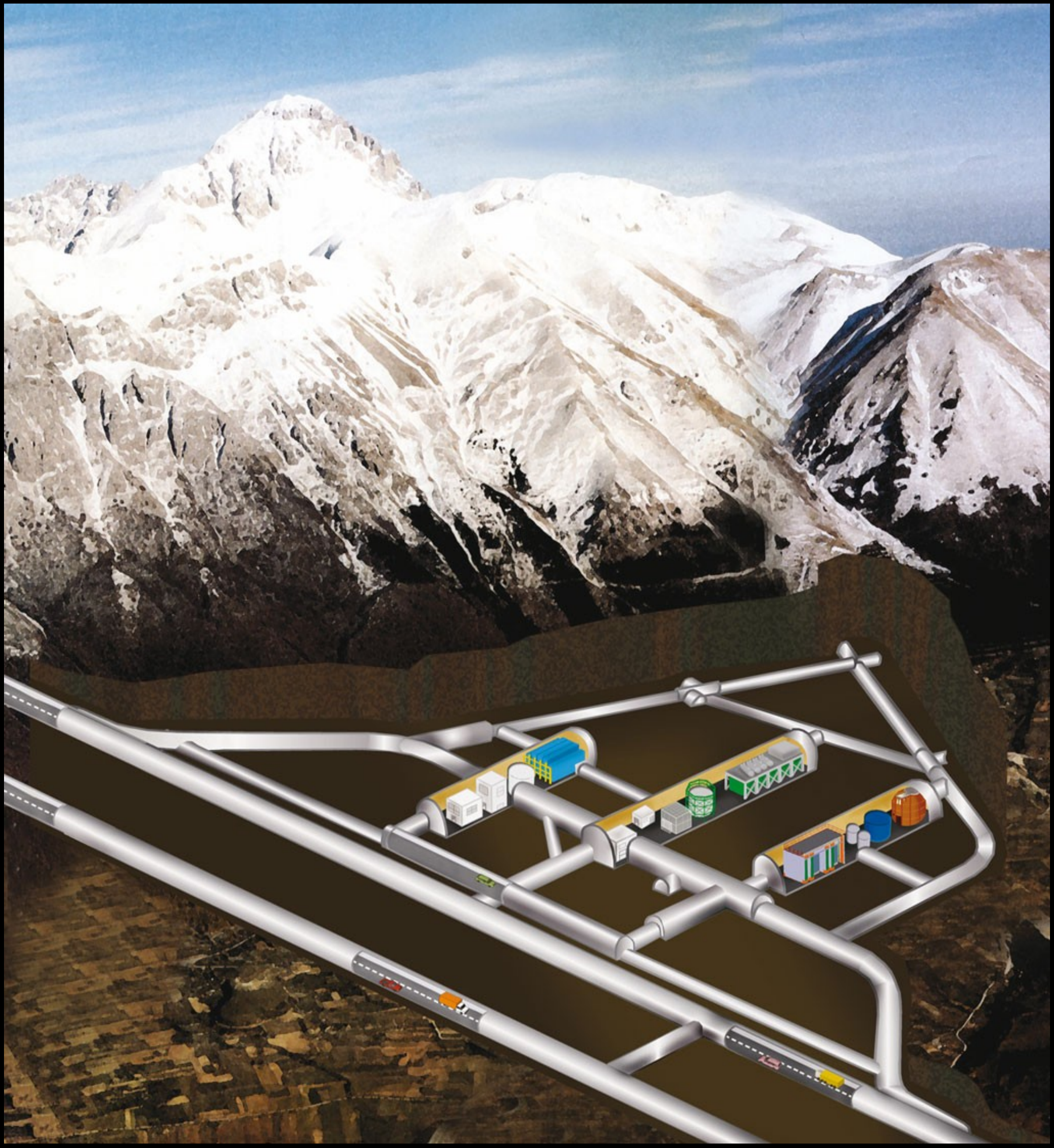
- Radiogenic backgrounds:
  → Clean construction
  → Active veto
  → Event discrimination

DarkSide-50



DarkSide-50 consists of three nested detectors located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy

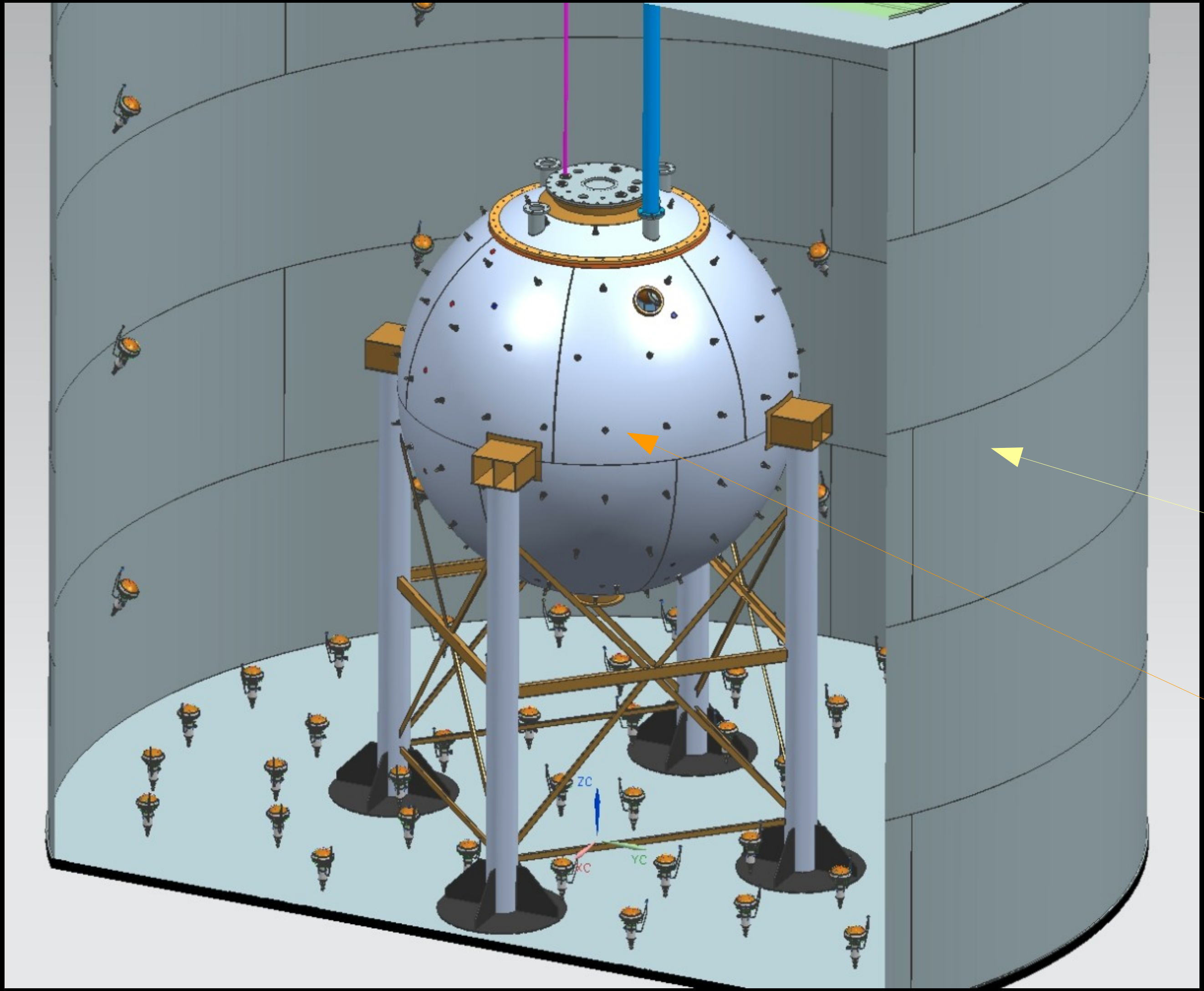
LNGS



- Home to many experiments:
  - → DAMA/LIBRA
  - → GERDA
  - → XENON-1T
  - → DarkSide
  - → Borexino
  - → CRESST
  - → CUORE
- Located at a depth of ~1300 m (3800 m.w.e.)

Muon flux reduced by a factor of ~10^6 relative to the Earth's surface

The Veto System

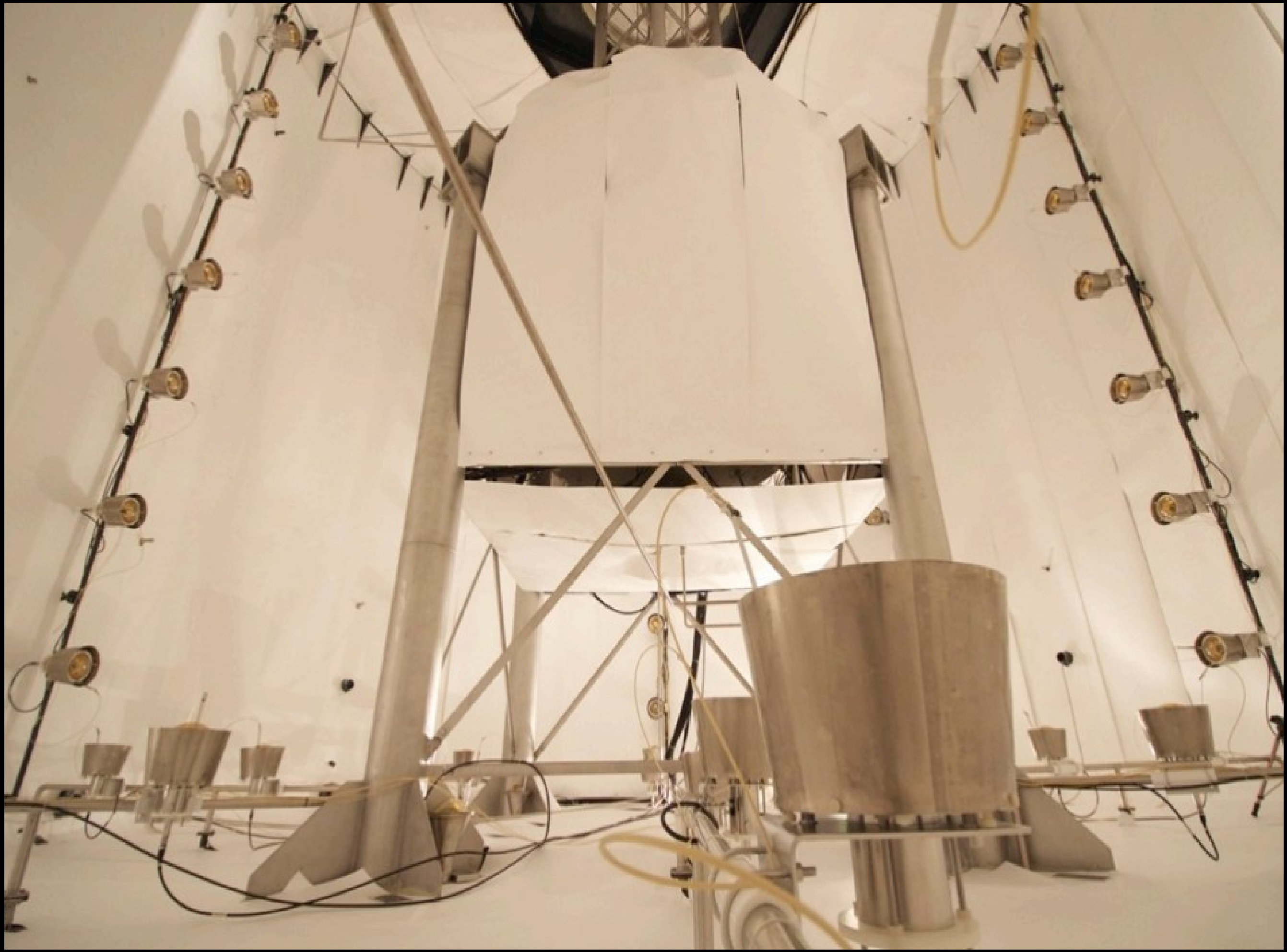


The DarkSide-50 TPC is housed inside two nested, active vetos:

the Water Cerenkov Muon Veto (WCV), and the Liquid Scintillator Neutron Veto (LSV)

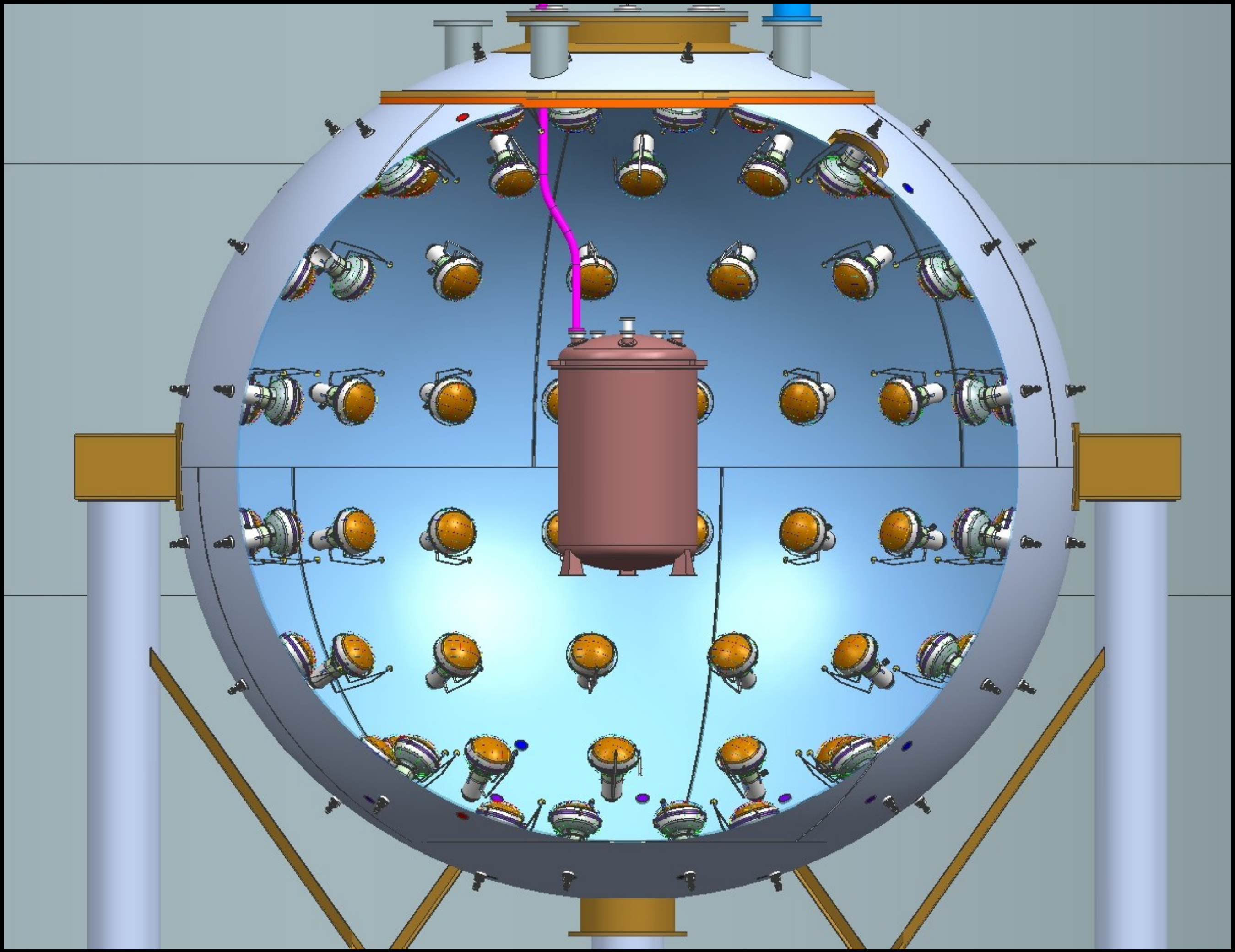
Water Cerenkov Veto (WCV)

- 10 m high, 11 m diameter cylinder
- Monitored with 80 PMTs
- Acts as *both* a passive neutron veto *and* and active muon veto



Liquid Scintillator Veto (LSV)

- 4 m diameter sphere
- Monitored with 110 PMTs
- Boron-doped scintillator



Boron-Doped Scintillator

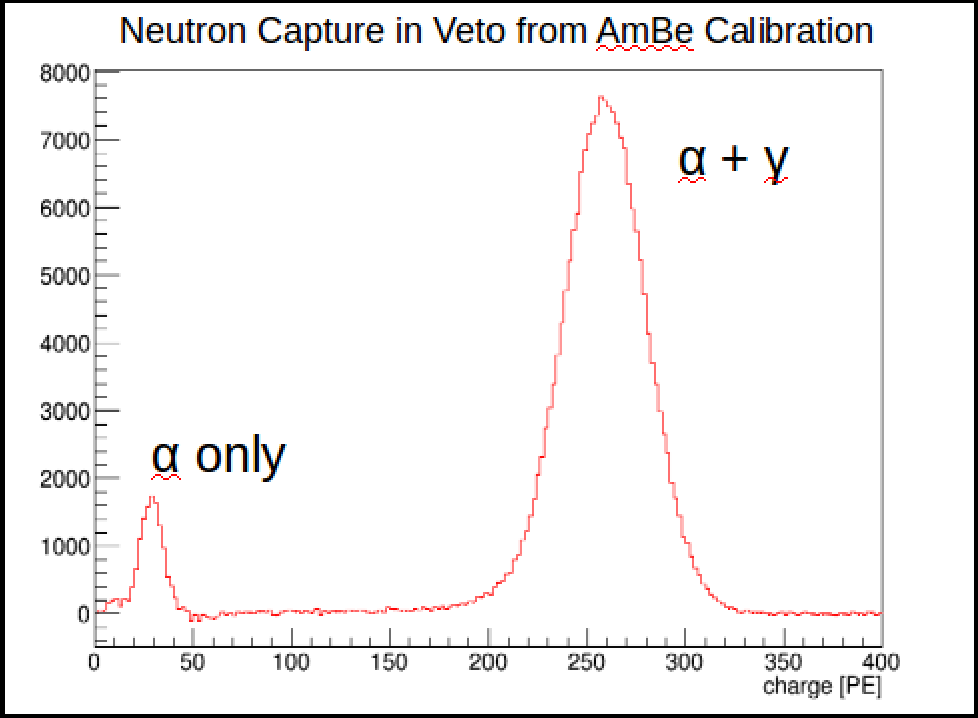
- The scintillator is doped with 5% trimethyborate (TMB)
- Boron has a high neutron capture cross section (3837 b) and captures neutrons via one of two channels:

$$^{10}B + n \rightarrow {}^{7}Li + \alpha \ (1.78\ MeV) \qquad (6.4\%)$$

$$\rightarrow {}^{7}Li^{*} + \alpha \ (1.47\ MeV),\ {}^{7}Li^{*} \rightarrow {}^{7}Li + \gamma \ (0.48\ MeV) \qquad (93.6\%)$$

- The vetoing efficiency of the LSV depends on the detection of the γ-free channel, due to quenching of the decay products

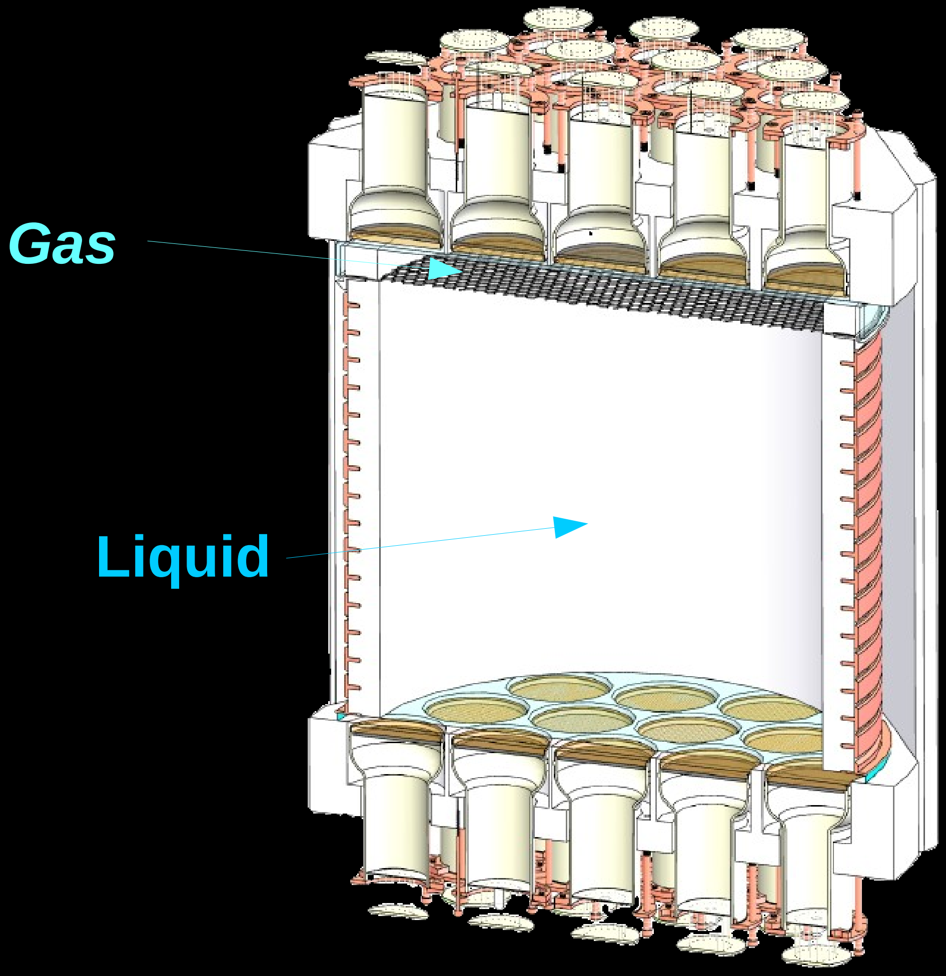
Efficiency of the LSV



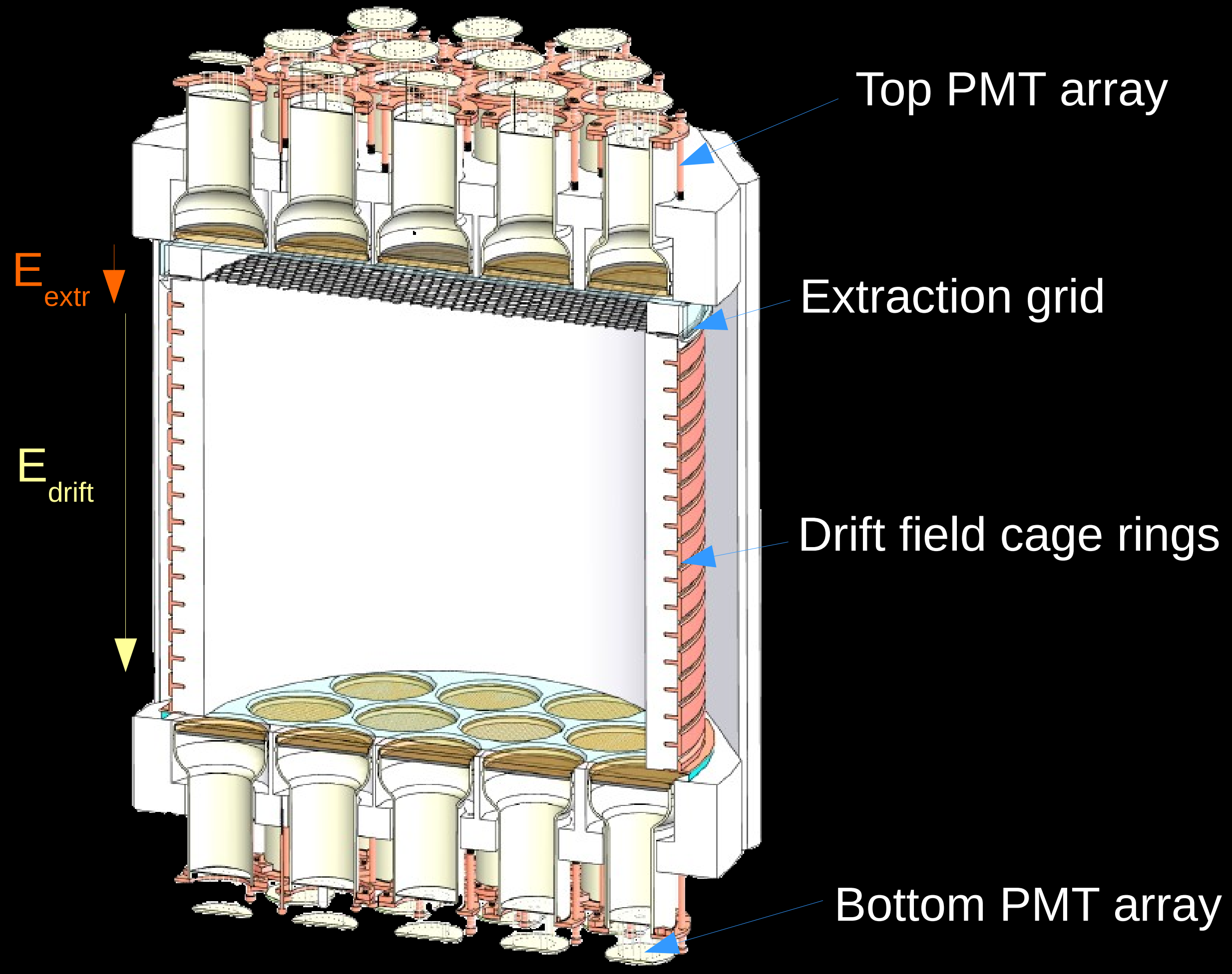
- The LSV was calibrated to nuclear recoils with a AmBe source in February 2015
- The α-only channel is clearly visible at ~30 PE, well above the detection threshold of a few PE
- The efficiency for detection of radiogenic neutron captures was found to be **at least 99.1%**
- Additional vetoing power is available by detection of the thermalization signal
- A calibration campaign with an AmC source was performed in December 2015 to study neutron thermalization – paper upcoming

Journal of Instrumentation, 11 (2016): P03016

Two-Phase TPCs



Two-Phase TPCs



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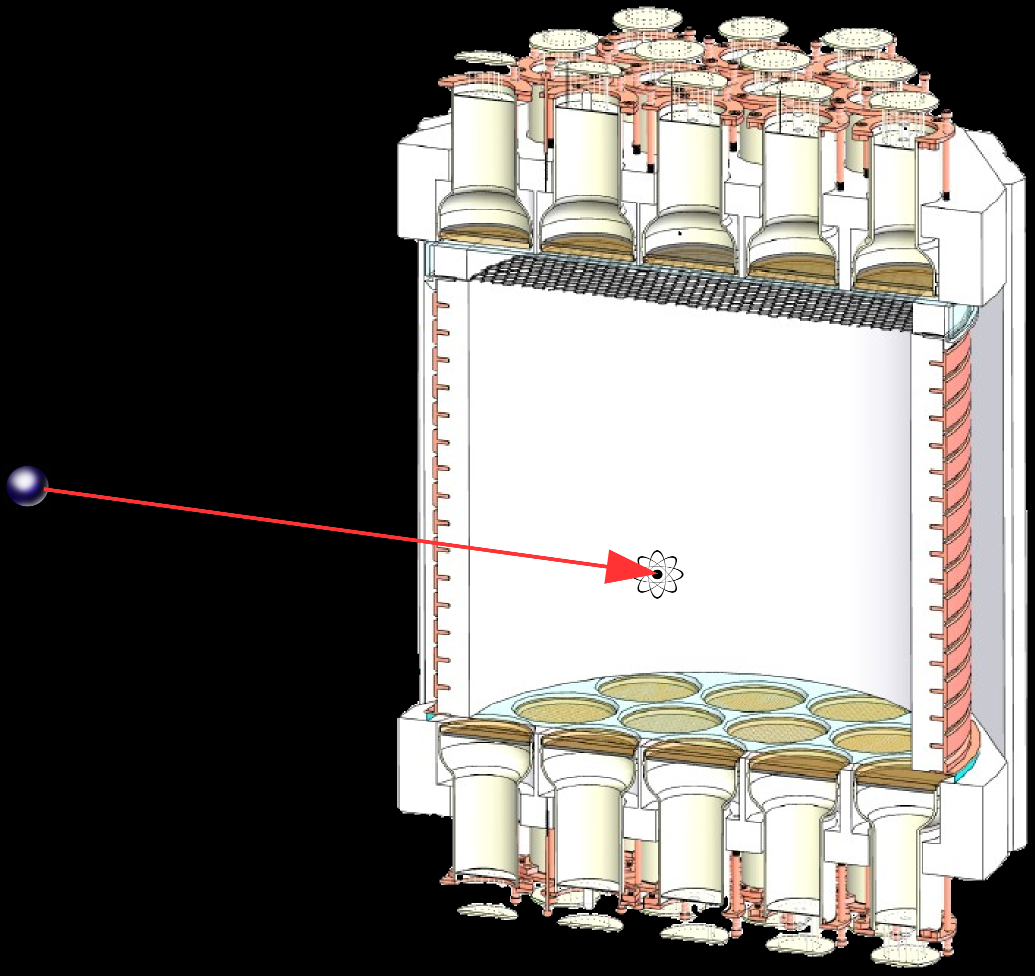

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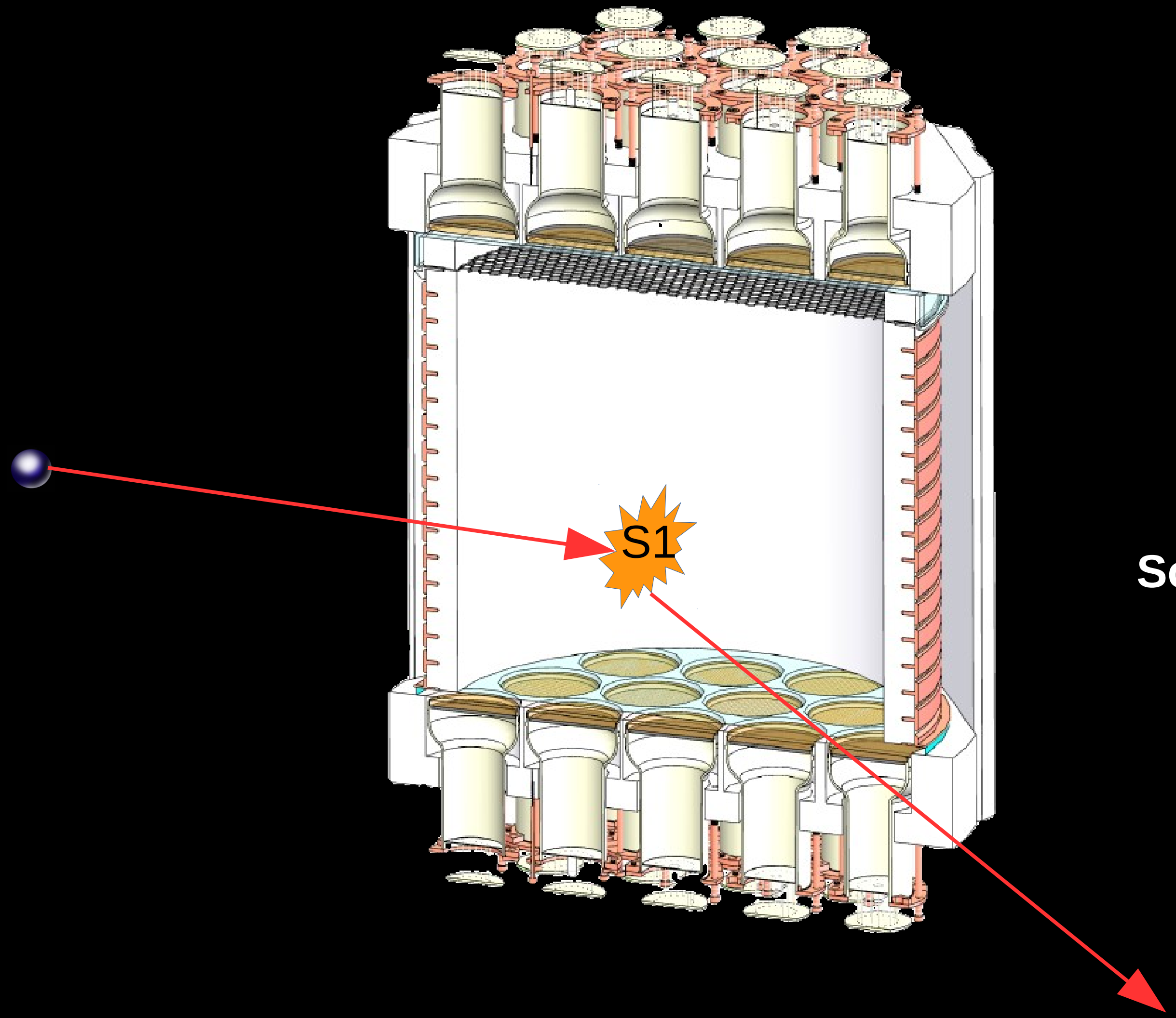
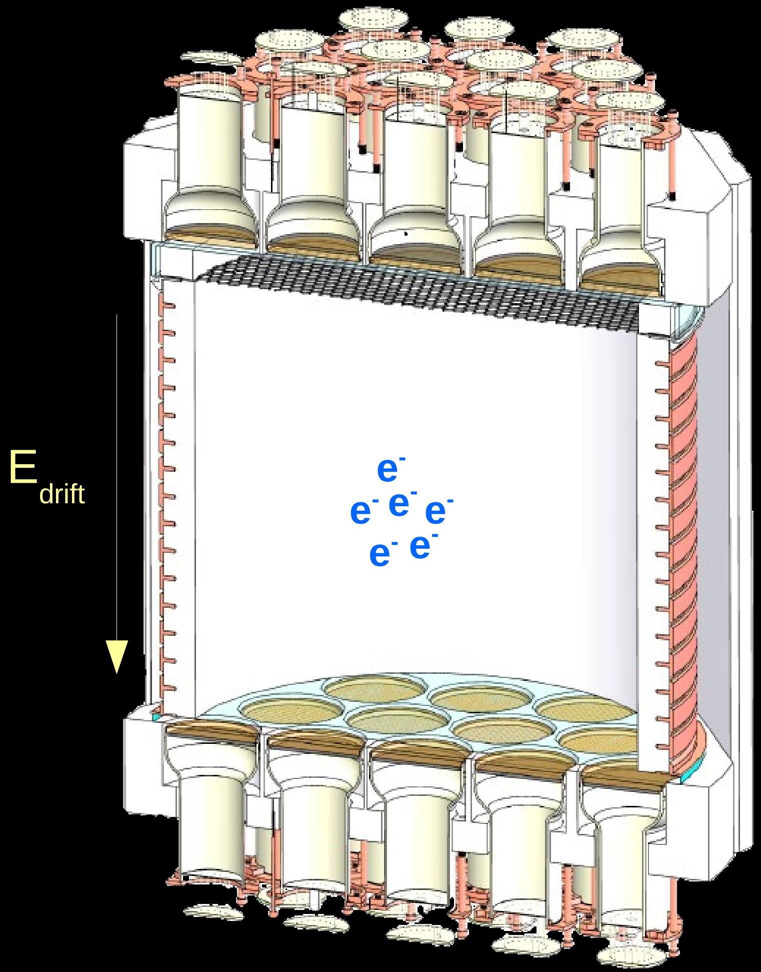


S1 = (primary) Scintillation signal

Two-Phase TPCs



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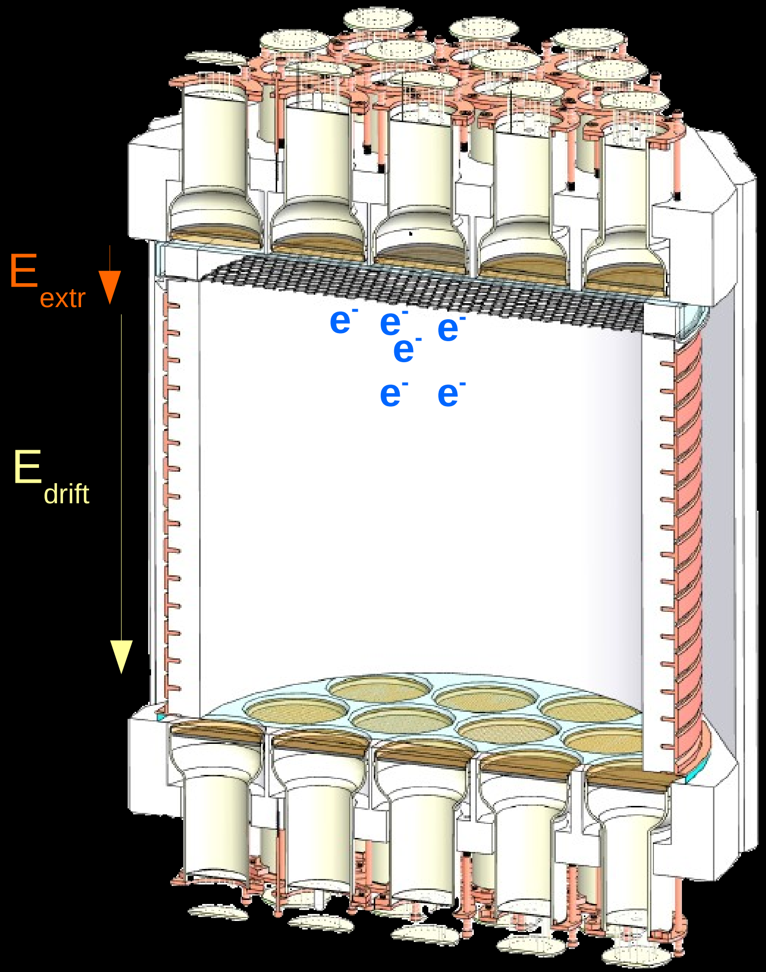

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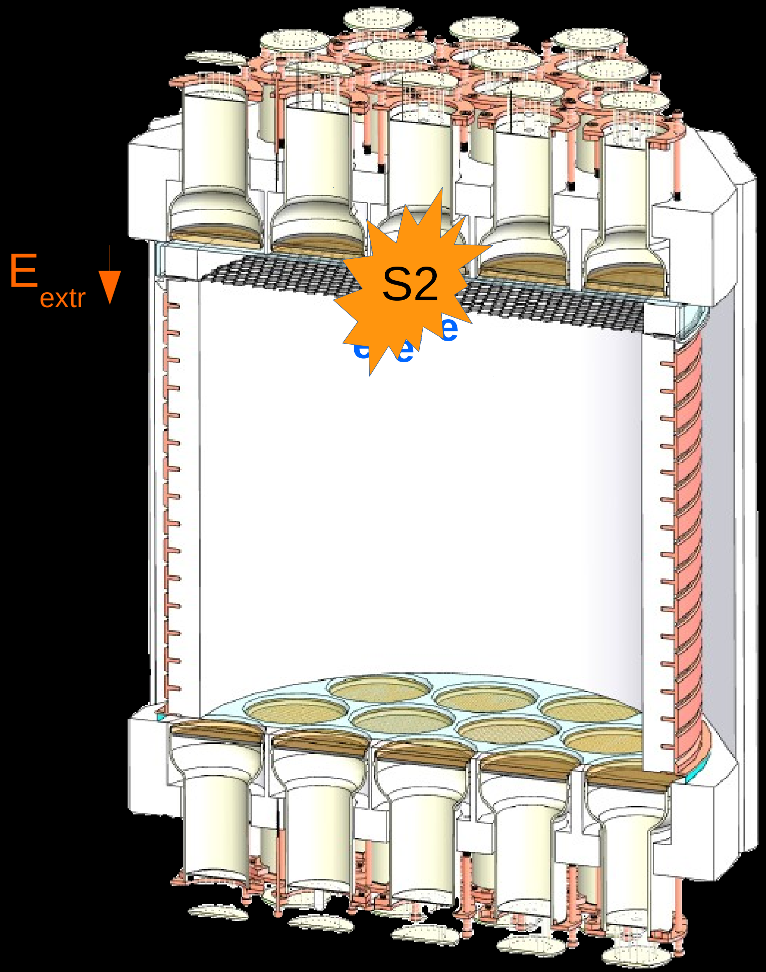
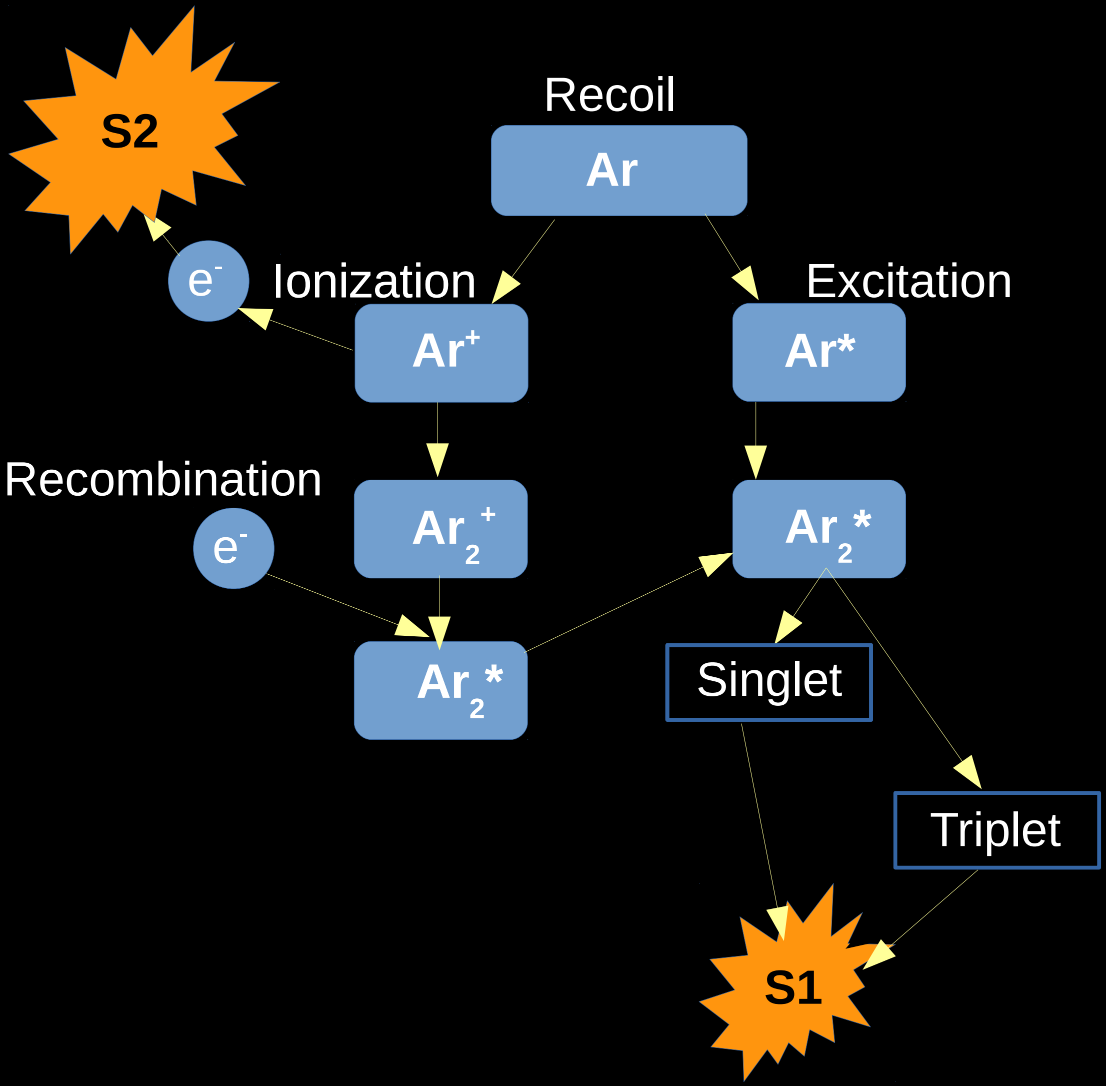


S2 = (secondary) Ionization signal

Scintillation in Liquid Argon



Singlet: τ = 7 ns

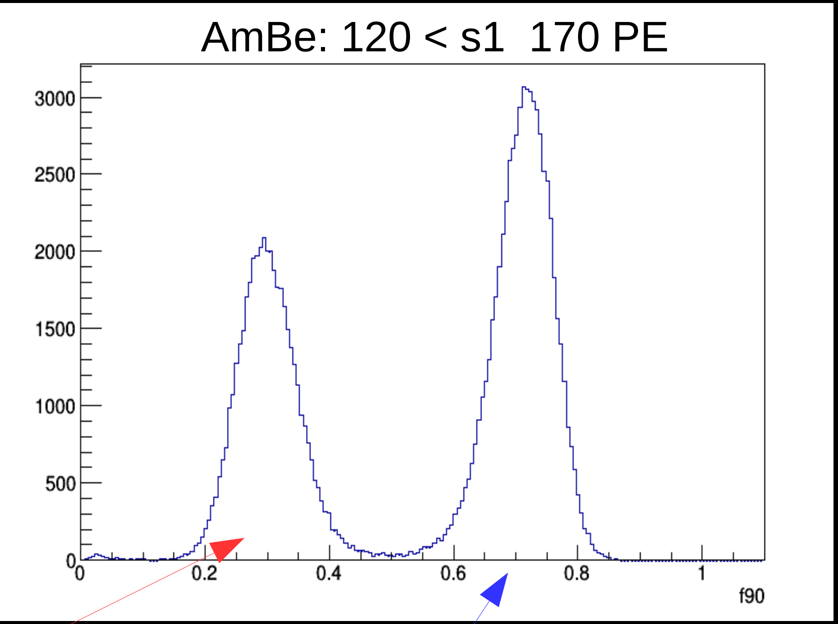
Triplet: τ = 1600 ns

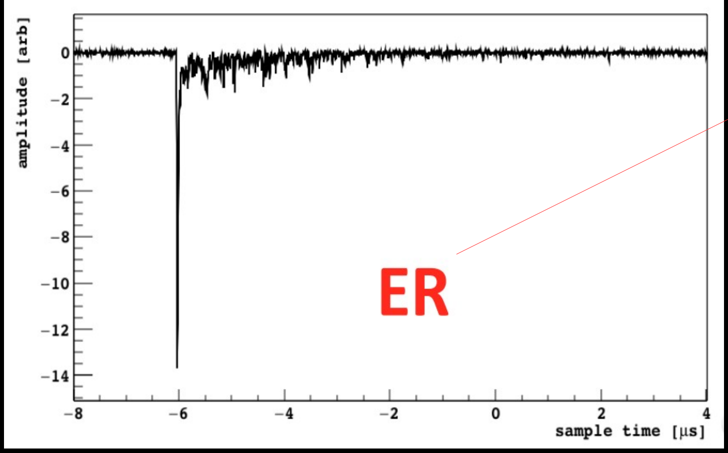
The ratio of singlet to triplet excitation states, as well as the relative level of ionization, depends on the nature of the interaction, ie: nuclear or electron recoil

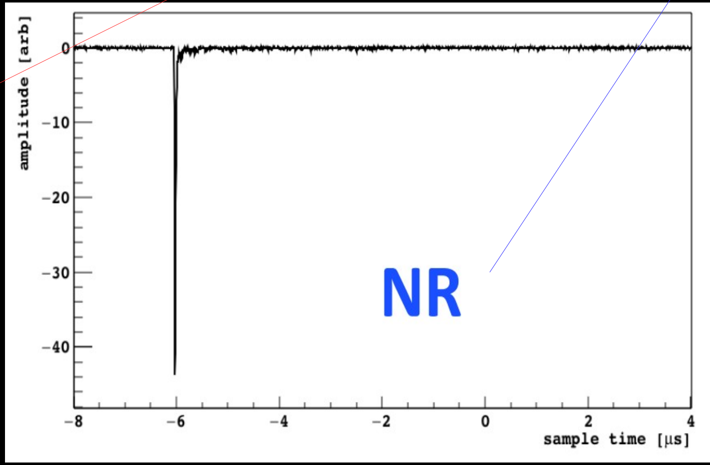
Pulse-Shape Discrimination in Liquid Argon

- Pulse shape is described by the f90 parameter:
  → Ratio of the light in the first 90 ns to the total light collected (over 7 μs)
  → NR: f90 ~ 0.7
  → ER: f90 ~ 0.3

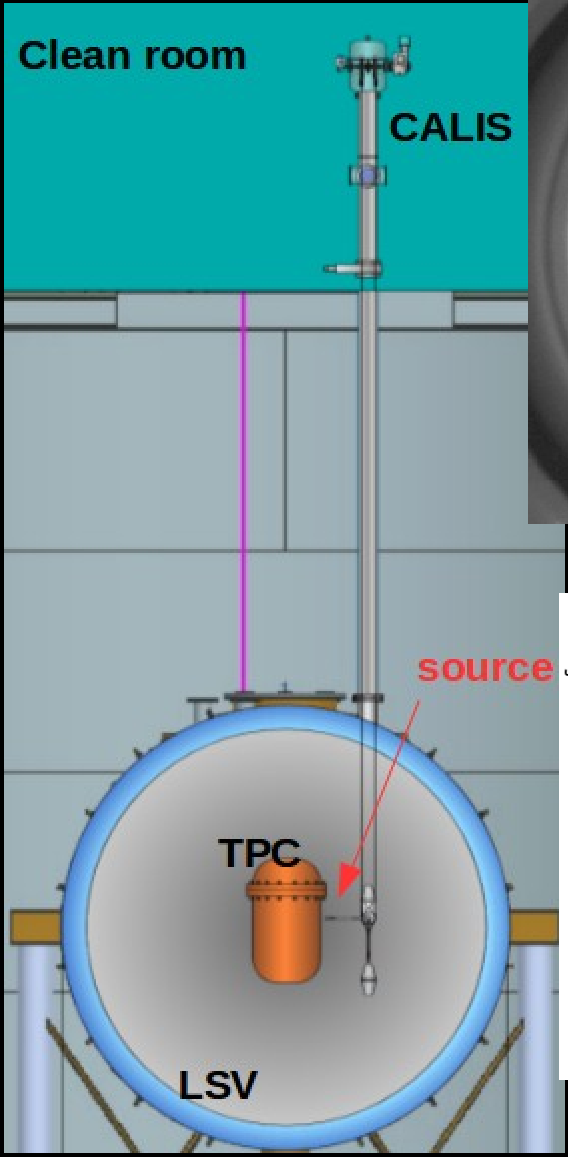
- *In argon, attain better than 1 part in 1.5×10^7 rejection of β/γ events from the S1 (scintillation) signal alone*

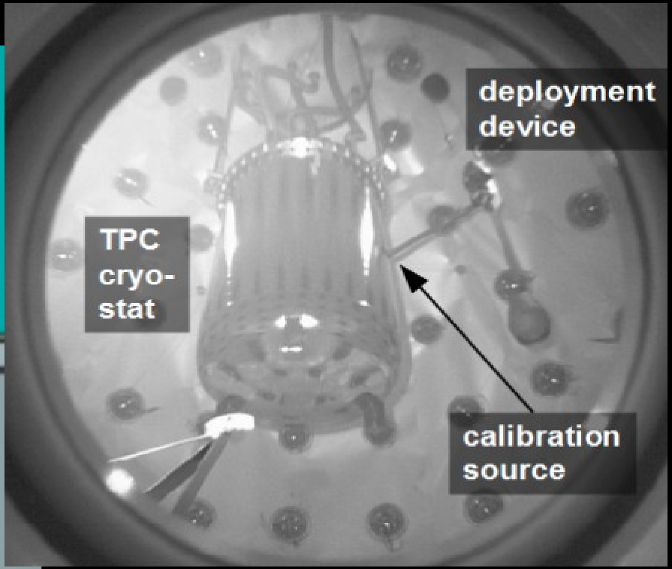


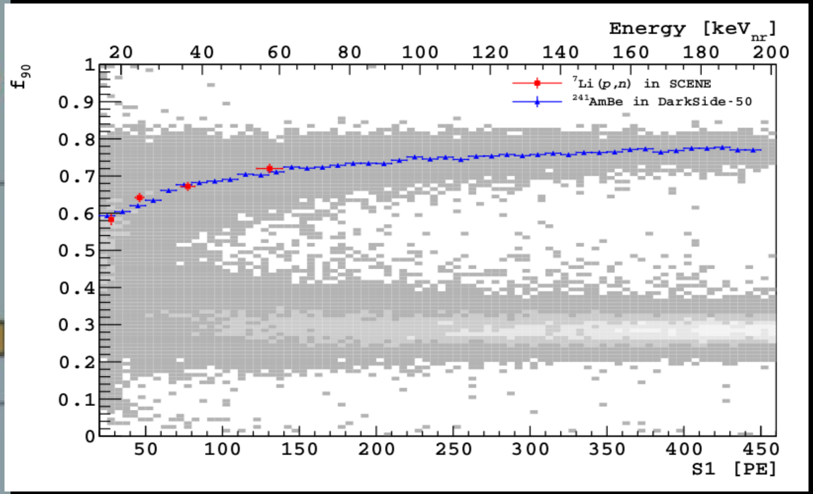




Calibration with External Sources







- CALibration Insertion System
  - Calibrates both the TPC and the LSV
- γ sources: ^{57}Co, ^{133}Ba, ^{137}Cs
  - Light yield, MC validation
- Neutron sources: AmBe, AmC
  - LSV efficiency, validate extrapolation of SCENE values to DarkSide

Using the LSV for Calibration Event Selection

- Radioactive neutron sources which are used for calibration typically have a high energy gamma correlated with the neutron
  → This introduces a large ER background to neutron calibrations in the TPC

- In the case of AmBe, 60% of neutrons have a correlated 4.4 MeV γ

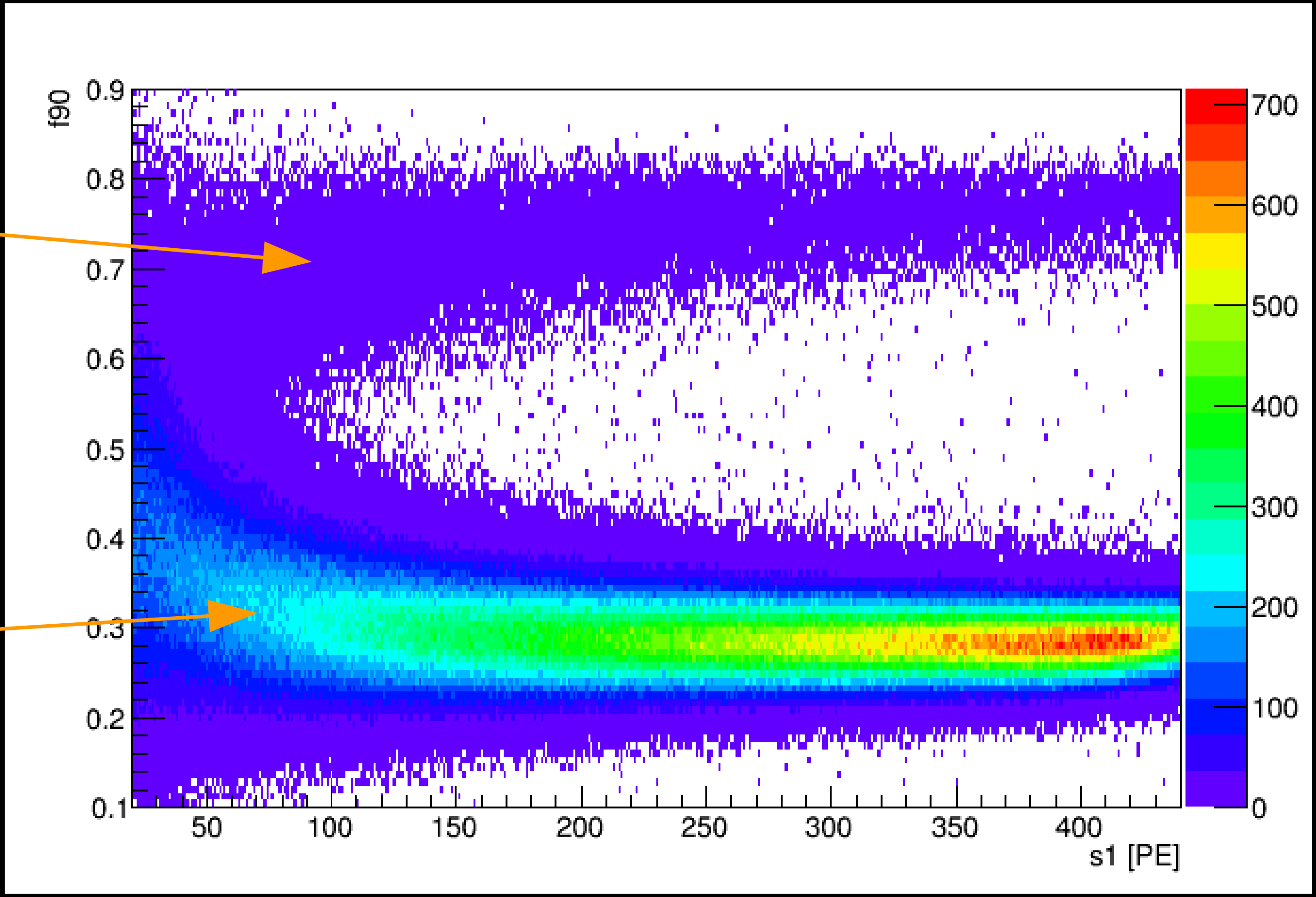
- Because DarkSIde-50 uses an active veto detector rather than passive shielding, these γs can be used to our advantage

  → *Select on events in which the 4.4 MeV γ deposits in energy in the LSV*

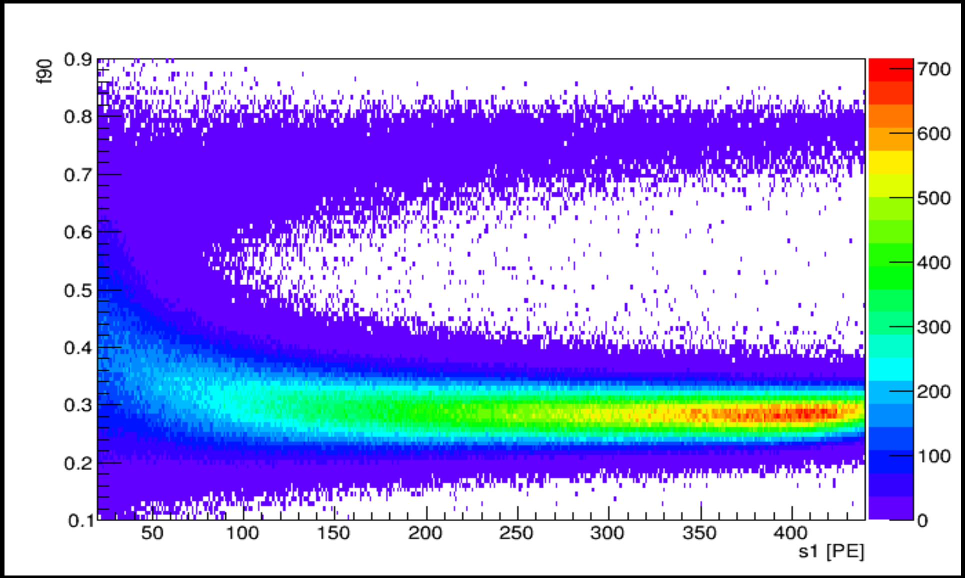
Using the LSV for Calibration Event Selection

Nuclear recoils (Neutrons)

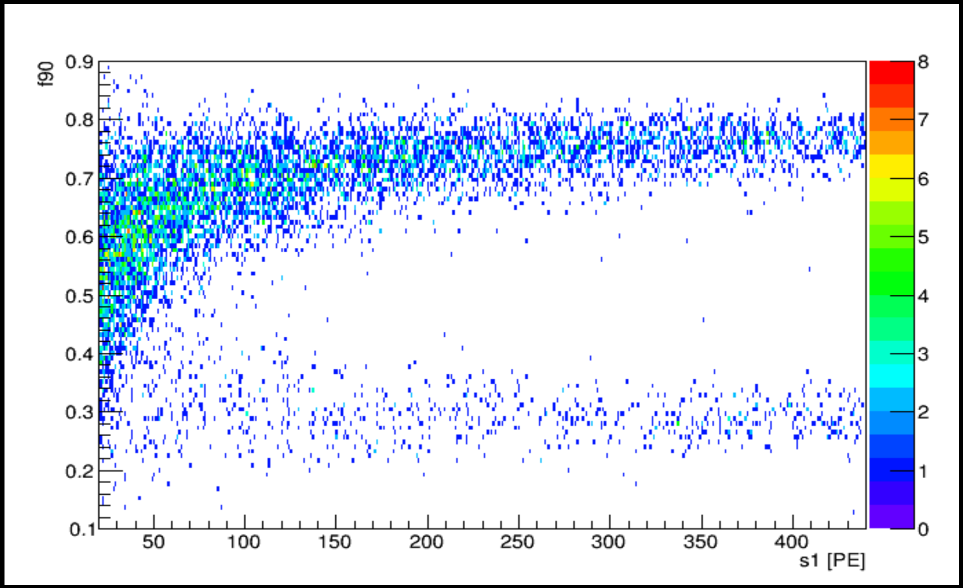
Electron recoils (Correlated γ's + intrinsic background from ^{39}Ar)



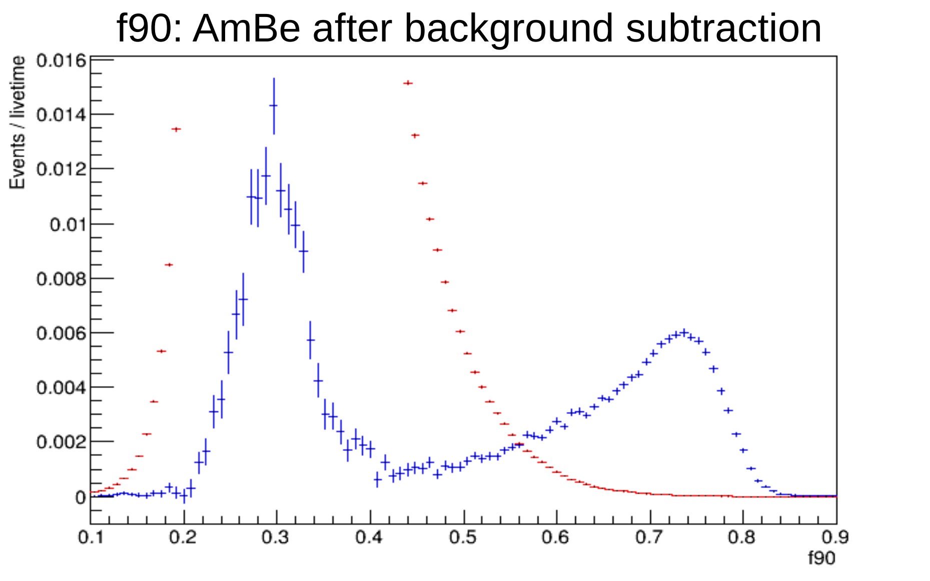
Using the LSV for Calibration Event Selection

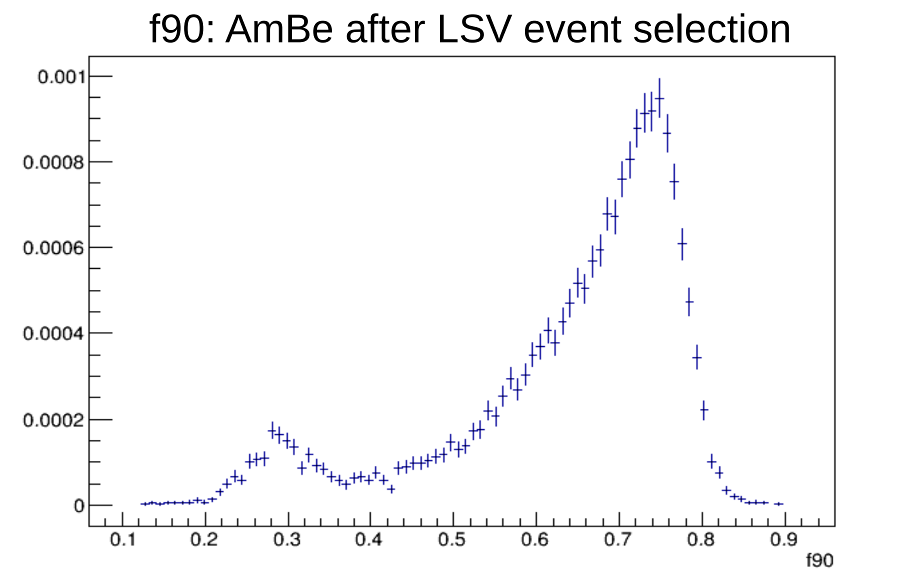


Before selecting on the γ in the LSV



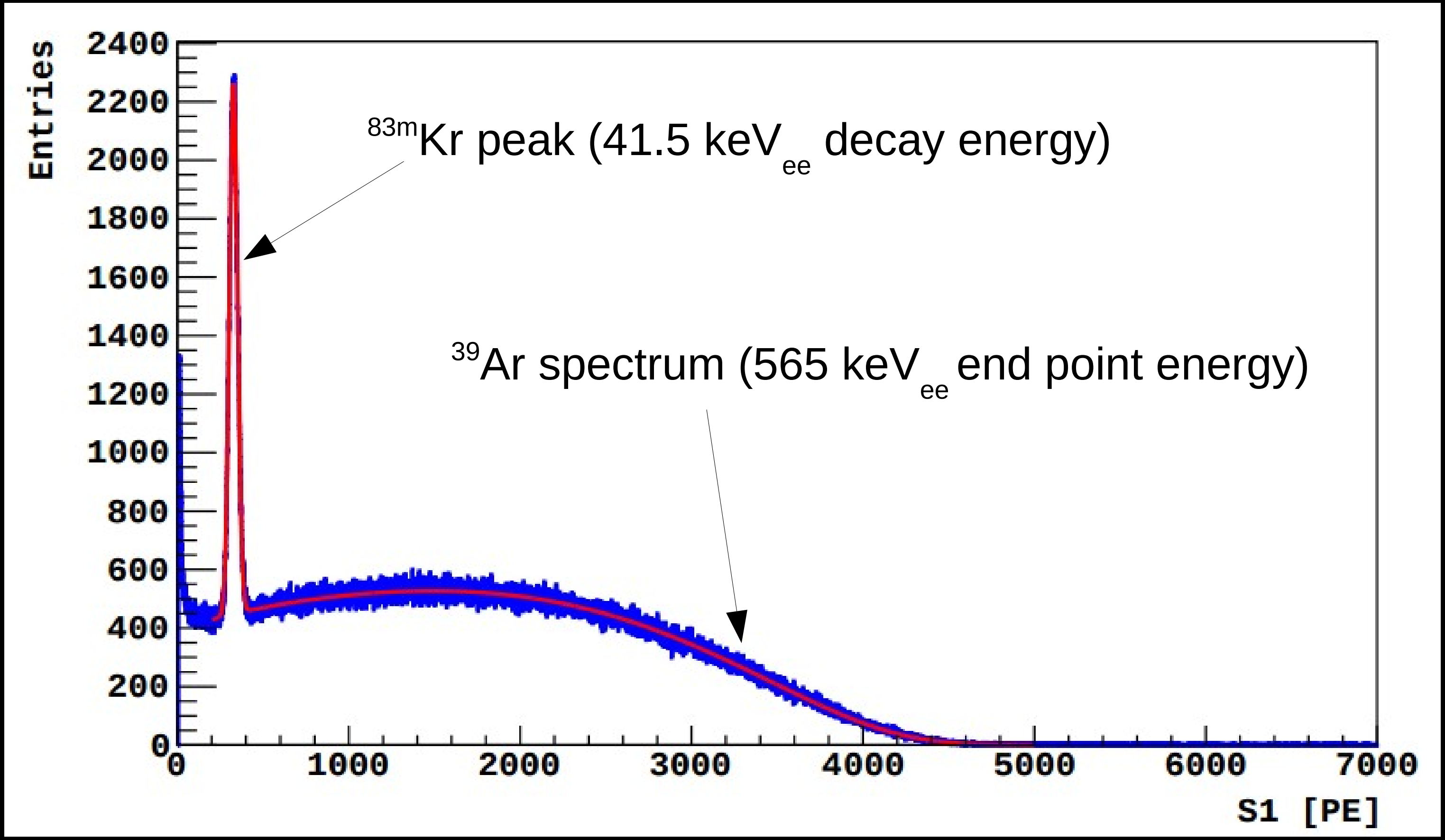
After selecting on the γ in the LSV





Internal Calibration

Detector light yield is determined from two internal calibration sources: ^{39}Ar (intrinsic to AAr) and ^{83m}Kr (half-life of 1.83 hrs, added to the Ar circulation loop)



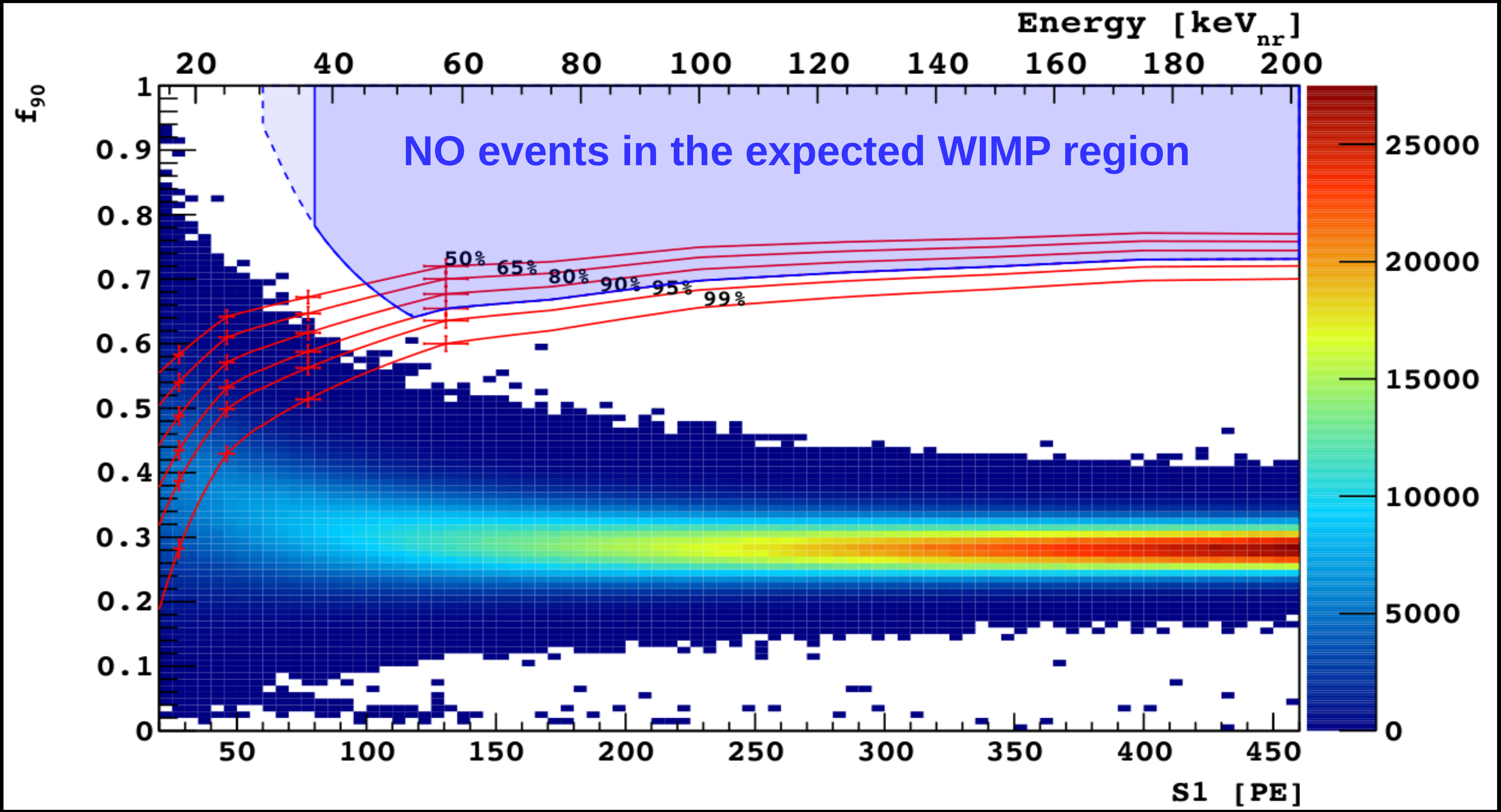
Light yield in AAr measured at:

***(7.0 +/- 0.3) PE/keV** @ 200 V/cm & **(7.9 +/- 0.4) PE/keV** @ null field*

WIMP Search Result with AAr

(1422 +/- 67) kg days of data (47 live days). Require events to be single scatter, no energy deposition in the veto

Upper limit of $\sigma = 6.1 \times 10^{-44}$ cm^2 at WIMP mass of 100 GeV/c^2 (spin-independent)



Phys.Lett. B 743 (2015) 456-466

^{39}Ar in Atmospheric Argon

- Although the ^{39}Ar content is an excellent high-statistics calibration source, its high activity and abundance in AAr (1 Bq/kg) limit the sensitivity of argon direct detection experiments

  → This is especially important as detectors increase in size

^{39}Ar in Atmospheric Argon

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  → This is especially important as detectors increase in size

Solution: Remove it!!

Underground Argon

- ^{39}Ar in the atmosphere is produced by cosmic ray activation, and has a half-life of 269 years
  → Argon sourced from deep underground is depleted in ^{39}Ar

- Beginning in 2009, underground argon (UAr) has been extracted from CO_2 wells in Cortez, CO
  → On-site enrichment increases concentration to ~5%

- Shipped to Fermilab to remove CO_2, O_2, N_2 and He via distillation column

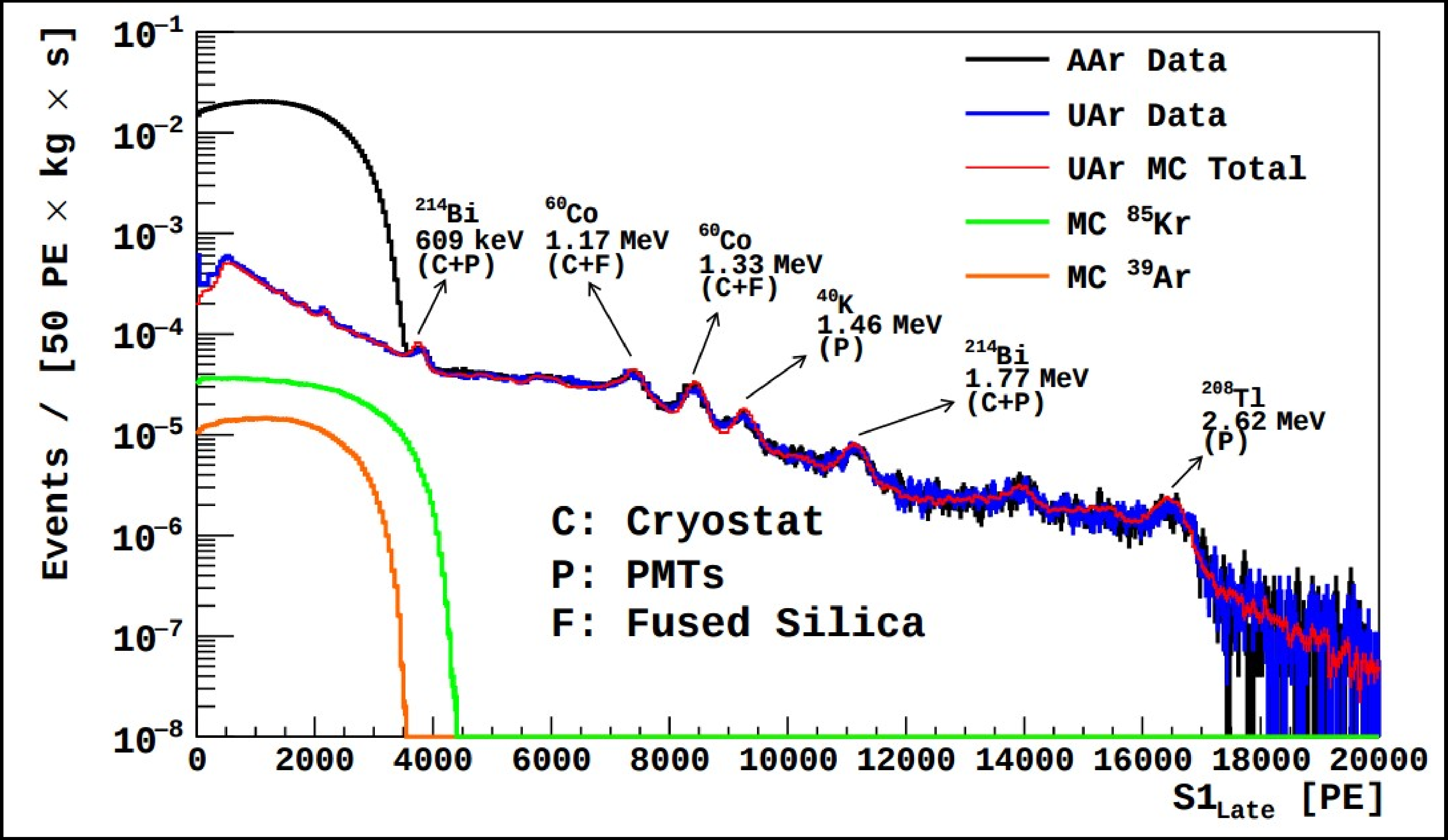
- Finally shipped to Gran Sasso, Italy

Underground Argon

- After 6 years of effort (!), 155 kg of UAr was produced
- DarkSide-50 was filled in April 2015

Underground Argon

Greater than factor of 1400 reduction in ^{39}Ar

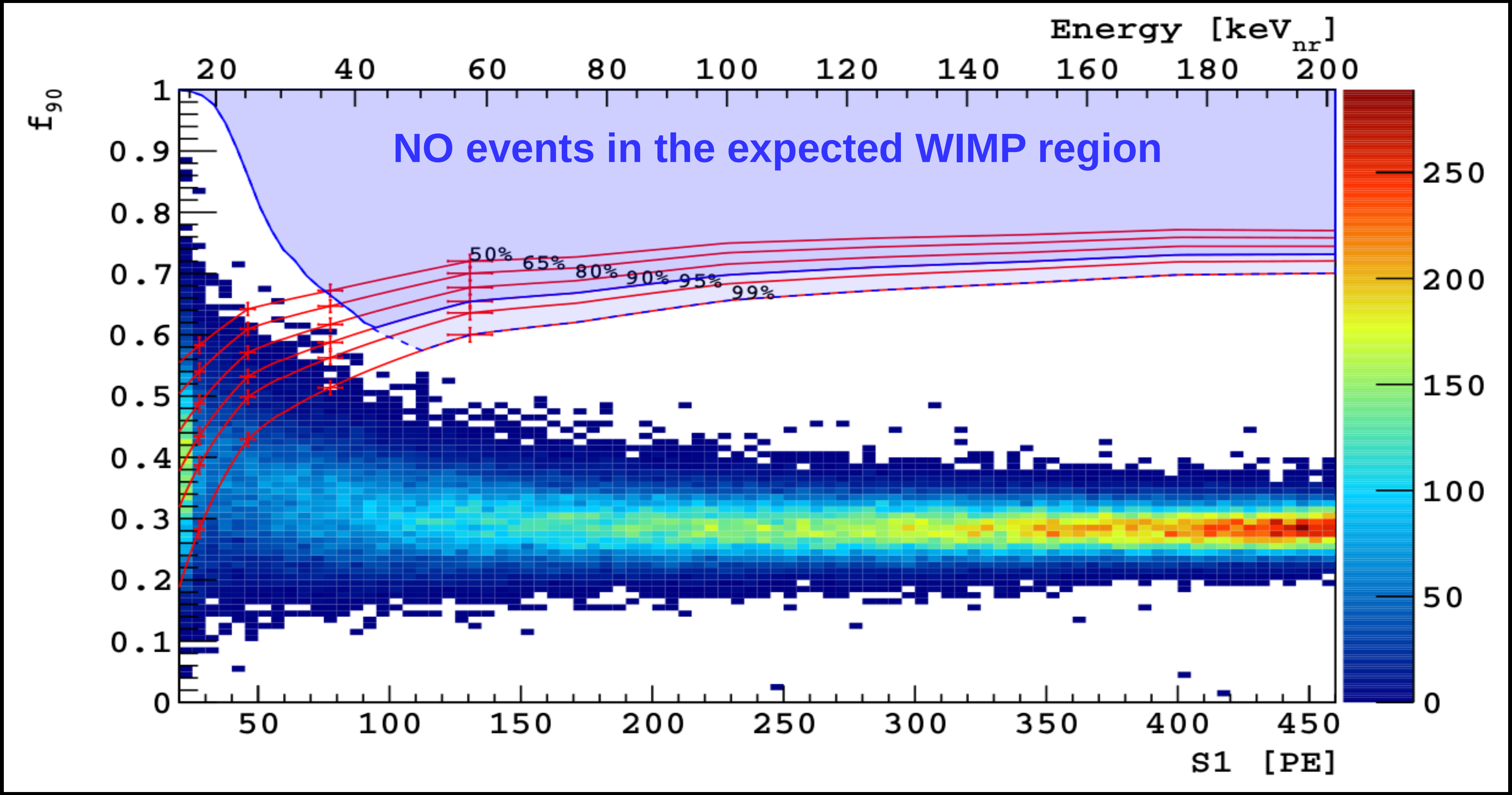


Live-time normalized data for UAr and AAr data at null-field

arXiv.1510.00702v3

WIMP Search Results with UAr

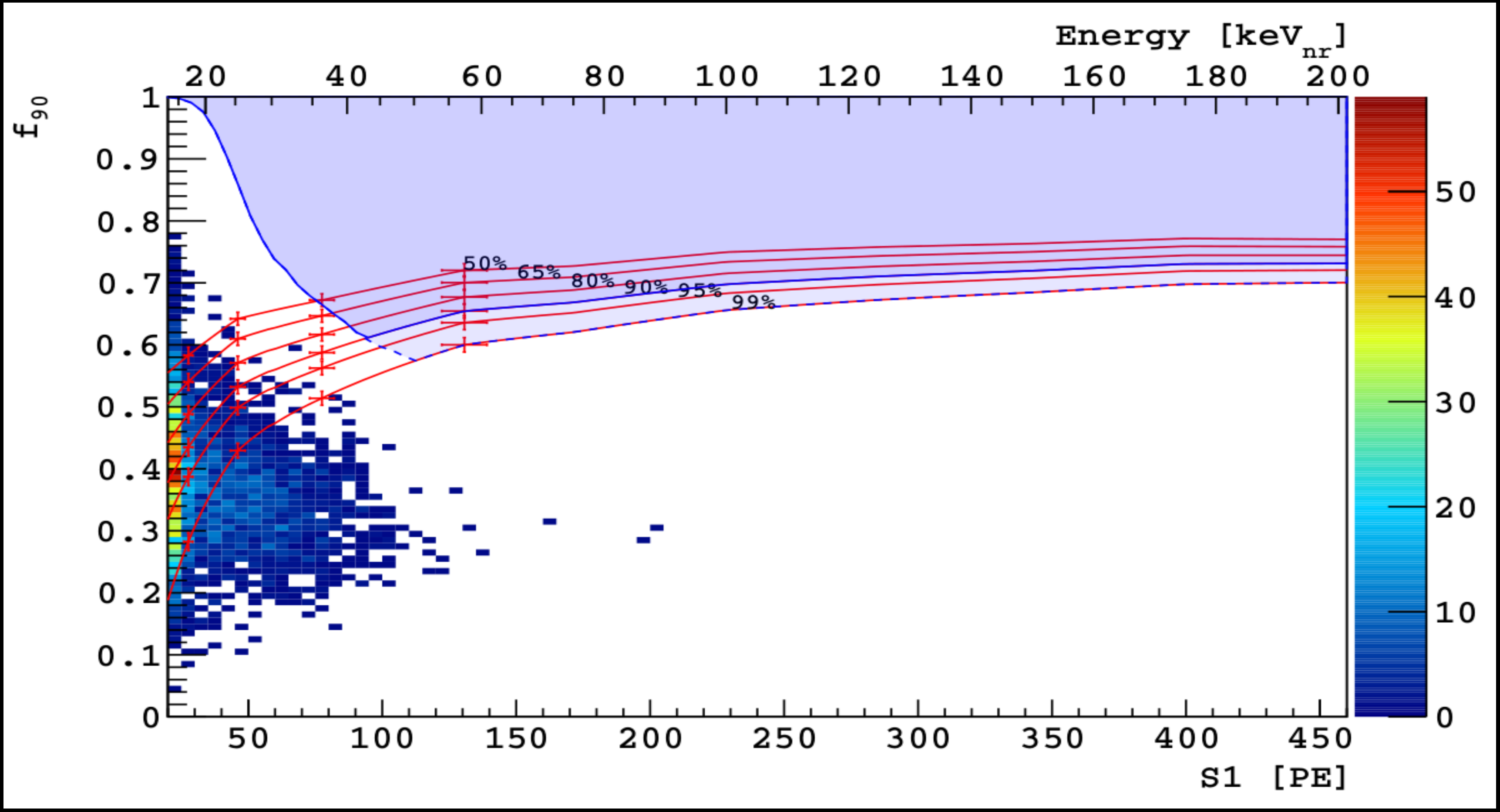
(2616 +/- 43) kg days of data (70.9 live days). Require single-scatter events, no coincident signal in the veto
Based on PSD from the S1 signal and a fiducial cut on z ONLY (no S2-based discrimination or cut on XY)



arXiv.1510.00702v3

WIMP Search Results with UAr

Additional background reduction is possible by including cut on S2/S1 (on median value for nuclear recoils) and XY fiducial cut (reconstructed radius less than 10 cm)



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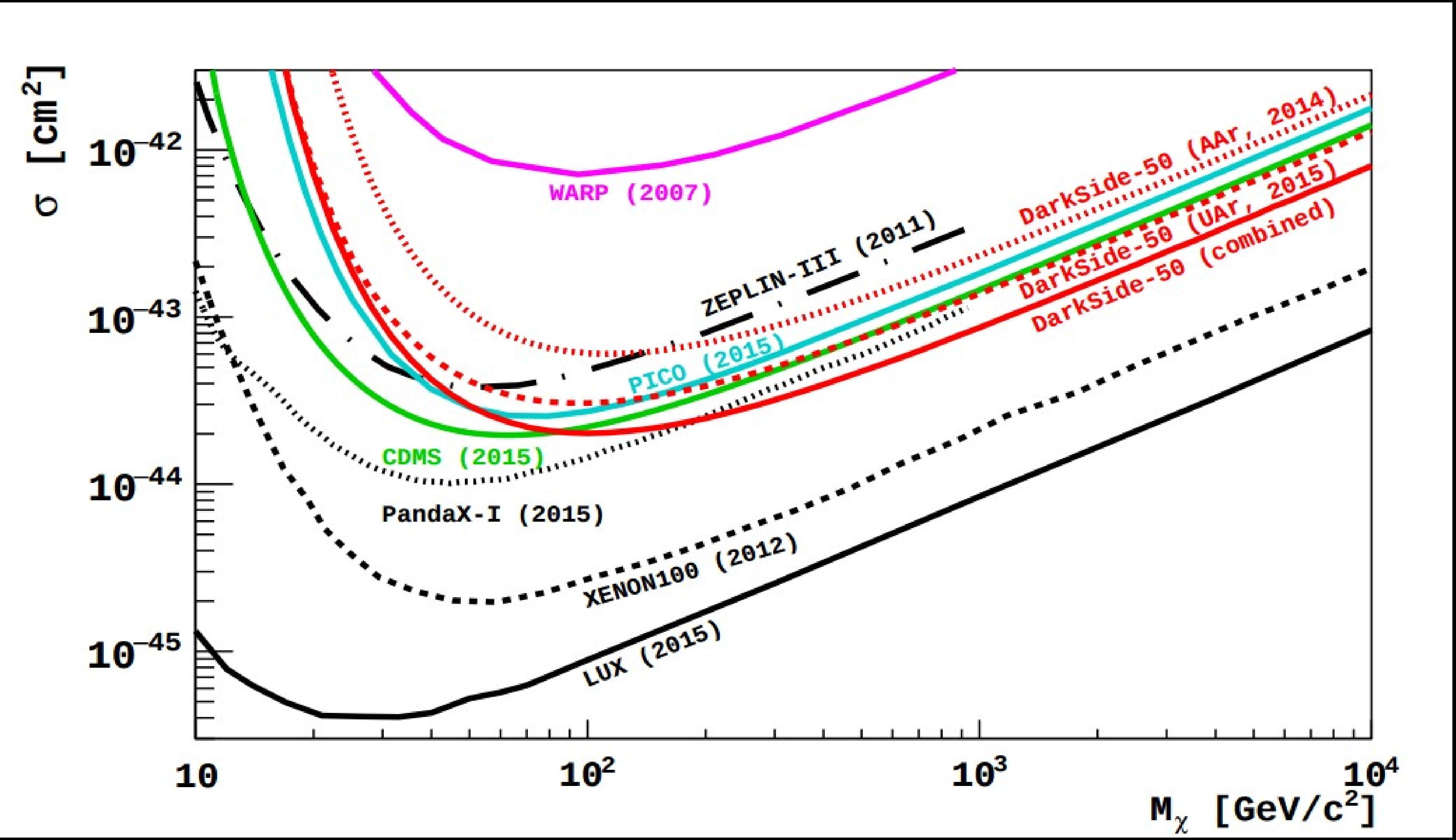
WIMP Search Results with UAr



Best limit on WIMP cross section from an argon target

arXiv.1510.00702v3

DarkSide-50: Present Status

- DarkSide-50 has met or exceeded all of its design goals
- Greater than 8 PE/keV light yield @ null-field
- Electron lifetime greater than 5 ms (compared to a maximum drift time of < 373 μs)
- ^{39}Ar contamination has been reduced by a factor of 1400
- DarkSide-50 is currently operating background free with a 3-year running plan
- First blinded WIMP analysis is coming soon

The DarkSide Program: Next Steps

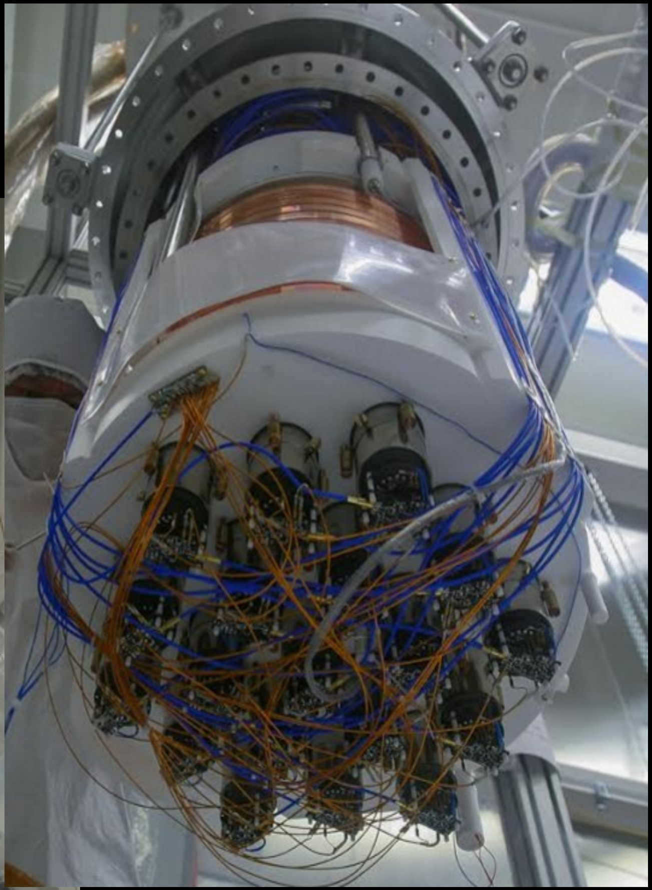
DarkSide is a multi-stage program:

DarkSide-10

The DarkSide Program: Next Steps

DarkSide is a multi-stage program:

DarkSide-50



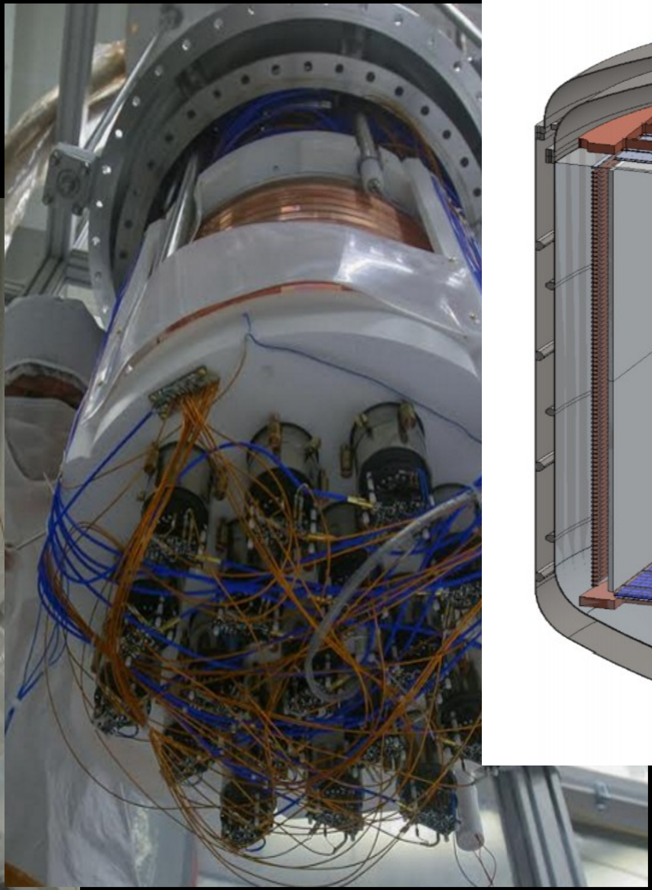
DarkSide-10

The DarkSide Program: Next Steps

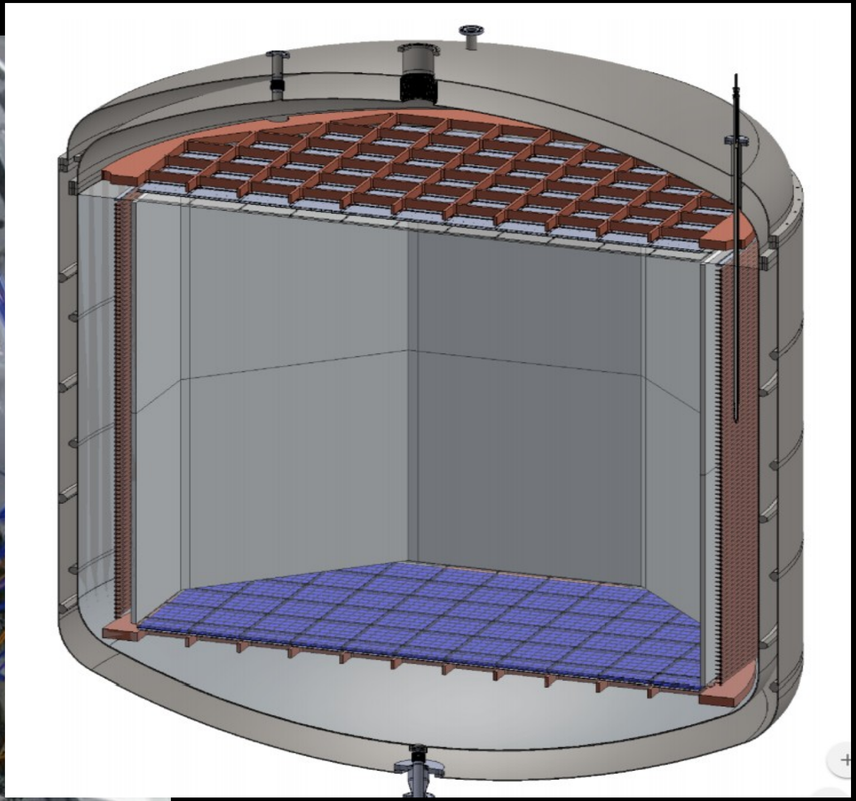
DarkSide is a multi-stage program:

DarkSide-10

DarkSide-50



DarkSide-20k

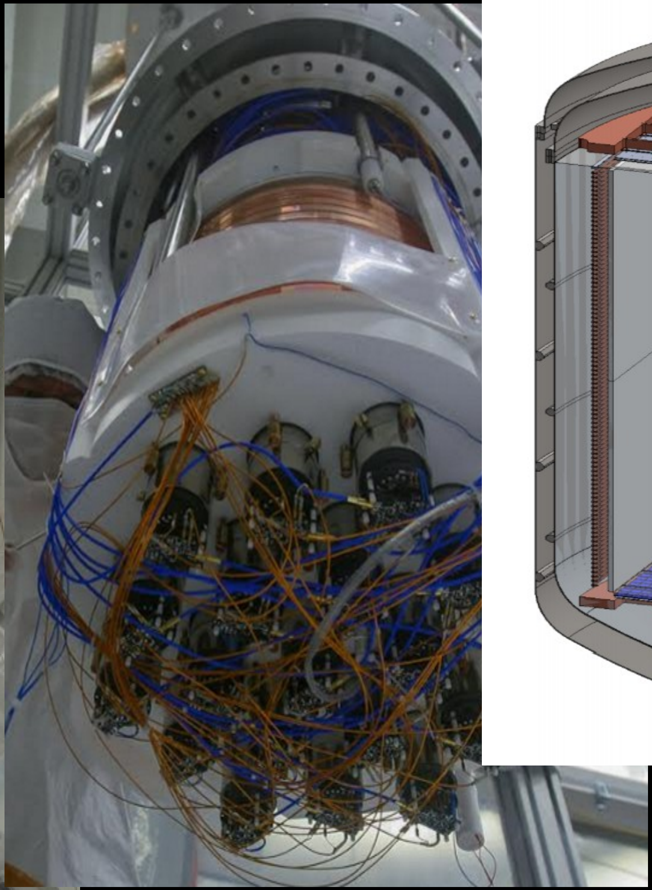


The DarkSide Program: Next Steps

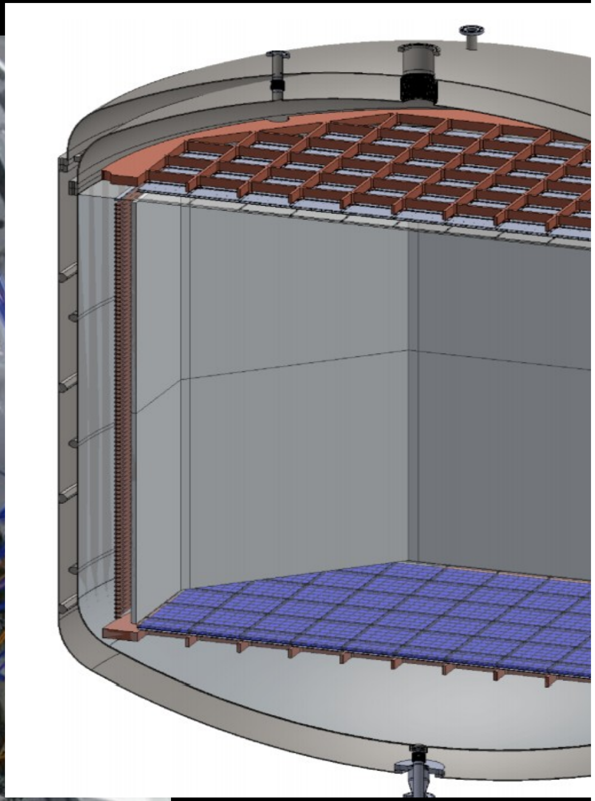
DarkSide is a multi-stage program:

DarkSide-10

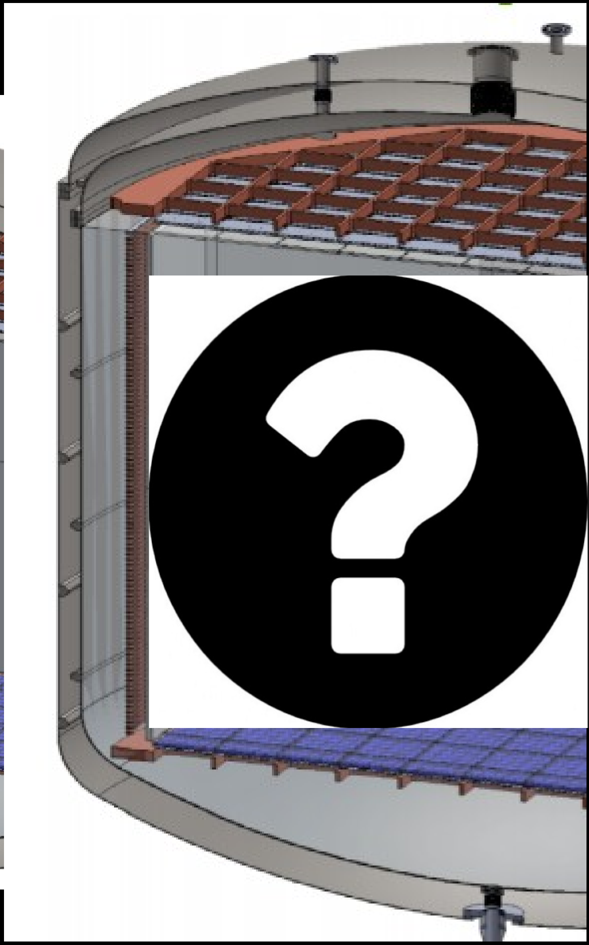
DarkSide-50



DarkSide-20k



ARGO



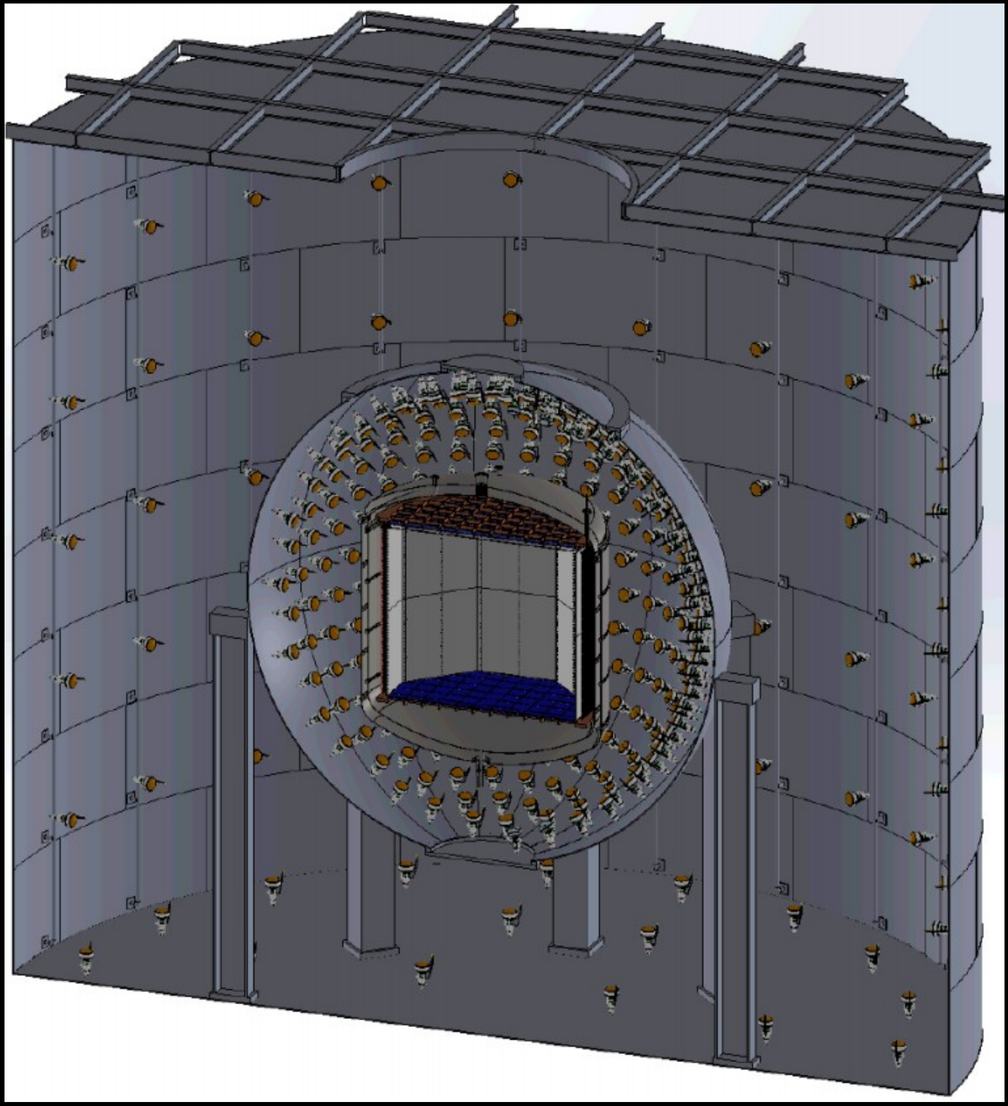
DarkSide-20k

- 40 institutions and growing

- Proposals submitted to INFN and NSF December 2015

DarkSide-20k

- Filled with 30 tonnes (20 tonnes fiducial) Depleted Argon (DAr – see following slides)
- Titanium cyrostat
- Monitored with SiPMs
- Same veto design as DarkSide-50
- Aggressive schedule for end of 2020 start
- Planned 100 tonne-yr background free exposure

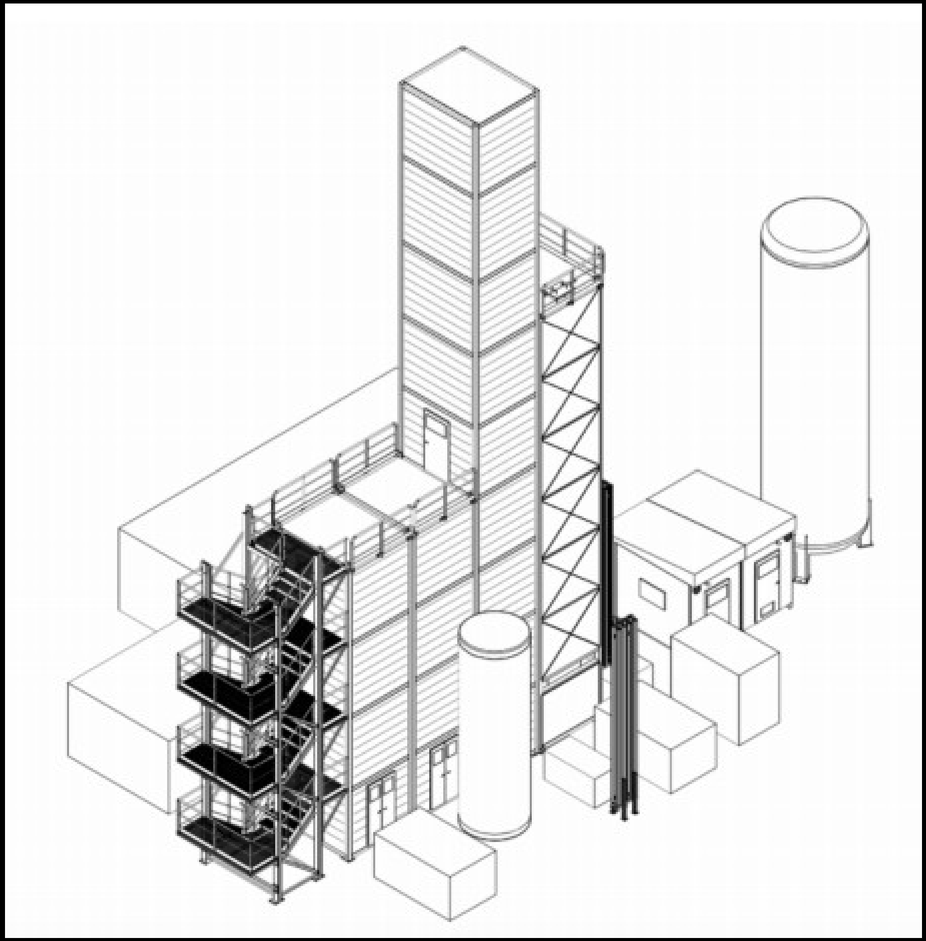


Future UAr Production

But it took 6 years to get 155 kg of UAr -
How will you get 30 tonnes???

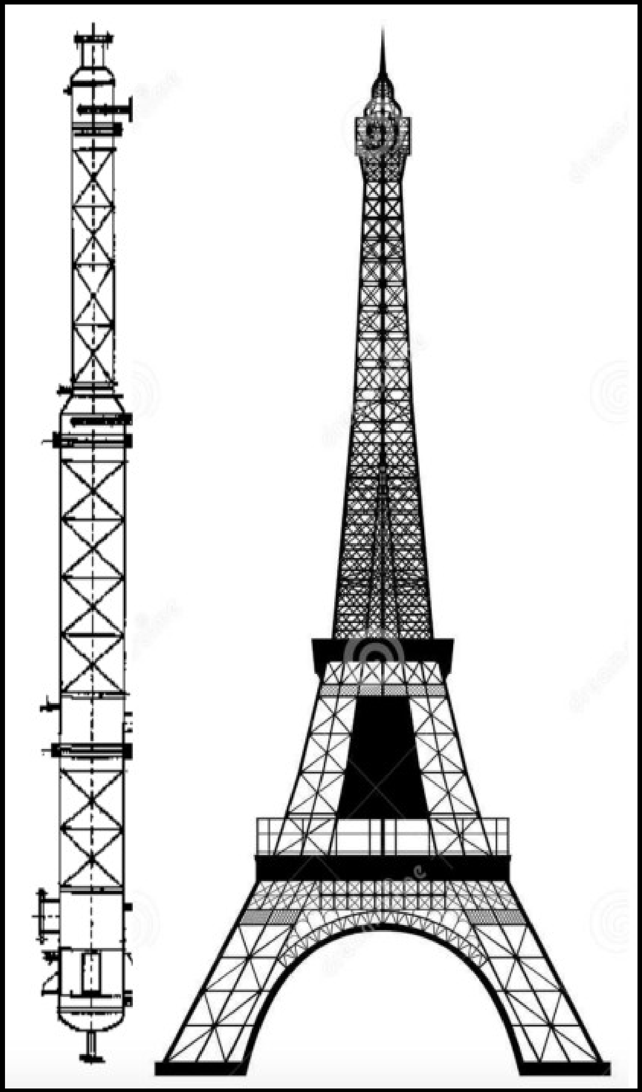
Urania

- Expansion of argon extraction plant in Cortez, CO
- Increase in production to **~100 kg/day** (currently ~0.5 kg/day)
- Argon is extracted and enriched at this location

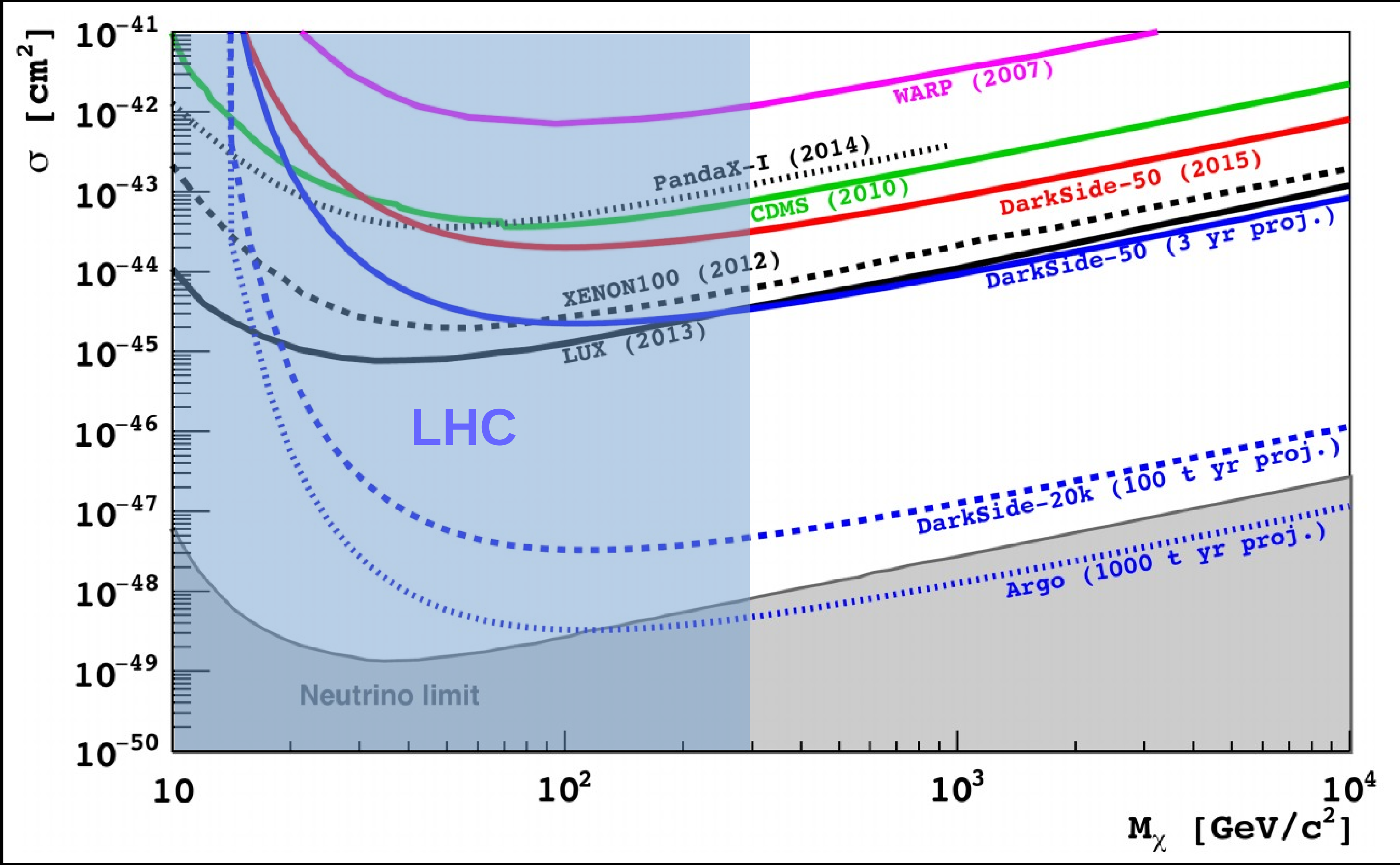


Aria

- Argon shipped from Colorado (Urania) to Sardinia (Aria)
- 350 m tall cryogenic distillation column located in the Seruci mine (Sardinia) for further purification of UAr → Depleted Argon (DAr)
- Expected factor of 10 reduction in ^{39}Ar *per pass*
- Project is supported by INFN, NSF, and Regione Autonoma della Sardegna



Future Physics Reach



Summary:

- DarkSide-50 is running smoothly, either meeting or exceeding its design requirements
  → The only direct dark matter experiment currently running background free

- The first WIMP cross section limit with underground argon has been set
  → Best limit with an argon target

- The next phase of the DarkSide program is in development for end of 2020 data taking

THANK YOU!

EXTRA SLIDES

Liquid Noble Targets

	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46